VOLUME XXIII SUPPLEMENT TO NUMBER 8

THE

JOURNAL OF GEOLOGY

NOVEMBER-DECEMBER 1915

SUPPLEMENT

THE LATER STAGES OF THE EVOLUTION OF THE IGNEOUS ROCKS

N. L. BOWEN
Geophysical Laboratory, Carnegie Institution of Washington

CONTENTS

INTRODUCTION
DIFFERENTIATION
- The Soret Action
- Gravitative Effect in a Liquid Magma
- Separation of Distinct Phases
  - Liquid Immiscibility in Magmas
  - Differentiation through Crystallization

THE ASSOCIATION OF DIABASE AND MICROPEGMATITE
- The System Diopside-Forsterite-Silica
  - Crystallization with Perfect Equilibrium
  - Crystallization with Zoning
  - Crystallization When the Crystals Are Free to Sink in the Liquid
  - Crystallization with Straining Off of the Liquid
- The System Anorthite-Forsterite-Silica
- Crystallization in Systems Involving the Plagioclases
- Crystallization of the Plagioclases in the Binary System
- Crystallization in the System Diopside-Anorthite-Albite
  - Crystallization with Perfect Equilibrium
  - Crystallization with Great Undercooling
  - Crystallization with Zoning
  - Crystallization with Subsidence of Crystals
  - The Effect of Rate of Cooling Summarized
- Conclusions to Be Drawn from the Investigated Ternary Systems

THE IMPORTANCE OF THE FORMATION OF BIOTITE
- Equilibrium in Silicate Liquids
- Equilibria in Magmas Indicated by Minerals Precipitated

THE CRYSTALLIZATION OF BASALTIC MAGMA

FIELD EVIDENCES OF THE CONTROL OF CRYSTALLIZATION IN DIFFERENTIATION

THE ALKALINE ROCKS
Nephelite Syenites and Related Types
Leucite-bearing Rocks
Escape of Thermal Waters
Other Conceptions of the Alkaline Rocks
IS BASALTIC MAGMA THE PARENTAL MAGMA OF ALL IGNEOUS ROCKS?
General Considerations
The Average Igneous Rock Compared with the Parental Magma
The Earlier Stages of Igneous Rock Evolution Not Revealed
THE NORMAL LINE OF DESCENT
Variations from the Stated Scheme of Crystallization
Monomineralic Rocks
The Order of Intrusion
Chilled Border Phases
The Rôle of Assimilation
SUMMARY AND CONCLUSION

INTRODUCTION

With the recent appearance of the books of Harker, Iddings, Daly, and von Wolff, it is natural to expect that the subject of our present knowledge of the igneous rocks and their origin has been thoroughly stated. Nevertheless, it has seemed to the writer that in these treatments of the subject, largely from the point of view of the field geologist, some questions have been left open which are capable of definite solution if the bearing of recent experimental work on these subjects is appreciated. Much of the experimental material was, indeed, not available when these books were in preparation. An attack on the problems of the igneous rocks from this latter point of view has led to a conception of their origin which is stated in the present paper. It is not hoped that the brief statement offered can possibly be the whole truth or that erroneous conclusions have been entirely avoided in a subject of such magnitude and complexity. Some hope is entertained, however, that the discussion offered may have a tendency to turn petrologic thought in a definite direction, and, perhaps, may suggest subjects of experimental investigation which may be pursued with likelihood of finding useful application of their results.

Differences in composition in associated rock bodies and in various parts of a single body have been referred by petrologists to two principal processes: assimilation of foreign material and differentiation. According to individual opinion, one or the other has been favored and some have proposed processes involving a combination of the two. A consideration of field facts, especially

in the light of the results hitherto obtained in the experimental study of silicate mixtures, has led the writer to believe that the former process, assimilation, is comparatively unimportant quantitatively, and that to understand the igneous rocks we must direct our energies toward the elucidation of processes of differentiation. Moreover, of the various processes of differentiation that have been proposed, it is considered that differentiation, or fractionation, by crystallization is vastly the most important. In the present paper the facts which have led to these conclusions are stated and a systematic petrogenic theory based on these conclusions is proposed.

DIFFERENTIATION

The term differentiation is applied to any process whereby a magma, without foreign contamination, forms either a mass of rock that has different compositions in different parts or separate masses that differ from one another in composition. The subject has been much discussed and apparently every conceivable process given a place as a factor in producing the observed results. In the following pages, discussion of these processes will be entered into only in so far as is necessary in order to indicate the reasons for believing that but one of these is of great importance, namely, crystallization and the movement of crystals relative to the remaining liquid.

Some investigators have considered that difference of composition in the magma itself, due to a temperature or a pressure gradient or to gravity, is the important factor. These continuous variations in the composition of the liquid, supported by Vogt, Iddings, and others, which are due to a *Diffusion oder Wanderung*[1] in a single liquid phase,[2] are to be carefully distinguished from a breaking up of the magma into immiscible partial magmas, i.e., a separation into two or more liquid phases, a process supported by Rosenbusch, Bäckström, and others.

Theoretically, continuous composition gradients should be established if sufficient time were available. However, in an actual case, there is reason to believe that crystallization begins long

[1] J. H. L. Vogt, "Über anchi-monomineralische und anchi-eutektische Eruptivgesteine," *Vidensk. Selsk. Skr.*, I Math.-Naturv. Kl., 1908, No. 10, p. 6.

[2] When a phase shows a composition or concentration gradient it can be treated in phase-rule considerations as divided into "regions"; see R. C. Tolman, *Jour. Am. Chem. Soc.*, XXXV (1913), 307.

before even very small effects due to these causes can be obtained. With crystallization, possibilities of differentiation are introduced which completely overshadow any of the possible effects of diffusion in a liquid phase.

THE SORET ACTION

The kind of composition gradient most commonly considered is that due to a temperature gradient, commonly known as the Soret action. It is generally assumed that a concentration takes place toward the colder parts of those substances whose crystallization is imminent. This assumption is designed to explain the observed fact that there is often a richness in the minerals of early crystallization toward the boundaries of igneous-rock bodies. But the Soret action takes place entirely in the liquid and is wholly independent of the solubility of the various substances in the liquid. There is therefore no reason to believe that the substances concentrated in the cold part would be those that are about to separate out. If a tube filled with a very dilute solution of common salt is warmed at one end, there will result a concentration of salt toward the cold end. If the whole tube is now gradually cooled, this same difference of temperature being maintained, a time will come when ice, not salt, crystallizes at the cool end. The substance concentrated at the cool end as a result of the Soret action was salt, the substance first crystallized there was ice. The Soret action has produced an effect in this case precisely the opposite of that which is commonly supposed to result from it. It is clearly unsafe to assume that the substances concentrated toward the cooling boundary would be those of early crystallization.

There is also a difficulty in obtaining a sufficient quantitative effect from the Soret action. Harker has demonstrated this truth by imagining certain temperature differences and calculating the possible composition differences that could be produced,[1] assuming that the concentration varies as the absolute temperature. This calculation shows that for a temperature difference of 100° at 1200° the relative concentrations would be as 1.07:1.[2] Even this esti-

[1] *The Natural History of Igneous Rocks*, p. 316.

[2] The Soret action has recently been reinvestigated for salt solutions and it has been found, as might be expected, that the simple relation deduced from osmotic-pressure laws does not hold (August Eilert, *Zs. f. anorg. Chemie*, LXXXVIII [1914], 1).

mate sets rather an upper limit which is probably many times the actual effect, for nearly all experimental investigations of the Soret phenomenon agree in placing the actual effect at much less than the amount calculated on the foregoing assumption.

The establishment of this fact should not be surprising, for the Soret effect does not, in reality, depend on a tendency of the solute alone to become more concentrated in the cold part. There is a tendency toward a greater concentration there of both solute and solvent, which is of course impossible, and if both obeyed the laws of ideal solutions, there could be no relative concentration of the one with respect to the other.[1] It is because the behavior of solute and solvent departs from the laws of ideal solutions, the one more than the other, that the Soret phenomenon is observed. The amount of the effect obtained as a result of this difference in degree of departure from the laws mentioned must necessarily be less than that calculated from the osmotic-pressure relation, which really involves the assumption that one substance obeys these laws and the other substance may be neglected, that is, is entirely unaffected by change of temperature.

Both theoretical considerations and experimental results indicate, therefore, that the actual Soret effect would be even less important than Harker's calculation would indicate—in short, quite negligible.

GRAVITATIVE EFFECT IN A LIQUID MAGMA

Of the same order of magnitude is the probable effect of the accumulation of the denser components of the magma solution in its lower portions, resulting in a composition gradient or density stratification in the liquid magma. An experiment made by Morozewicz has sometimes been cited as a proof that the extent to which this process may take place even in a crucible is very considerable, but a consideration of the conditions of the experiment shows that this conclusion is unwarranted.[2] In the experiment referred to, a sample of granite was fused or rather partly fused and, after cooling, analyses were made of the glass from the top and from

[1] See Bäckström, *Jour. Geol.*, I (1893), 774–75.

[2] J. Morozewicz, *Tscherm. Min. Pet. Mitth.*, XVIII (1898), 232.

the bottom of the crucible. The analyses showed a considerably larger percentage of silica in the upper portion, but it was also noted that there were grains of undissolved silica floating in the upper part. With silica in process of solution near the top, it would be a marvel indeed if the liquid in the upper part was not more siliceous than that in the lower, when the extreme viscosity of the liquid, and the consequent impossibility of diffusion and convection of sufficient vigor to maintain uniformity, are considered. Morozewicz' figures show also that there was a greater concentration in the lower portion, as compared with the upper portion, of iron oxide and the alkaline-earth oxides and a lesser concentration of the alkalis. The natural explanation of this is that some of the alkaline feldspar collected in the upper portion in exactly the same manner as the grains of quartz. After its solution, which for the alkaline feldspar happened to be complete, apparently, diffusion and convection were unable to establish uniformity of composition in the liquid. It should be noted, moreover, that the percentage of iron oxide and of lime was greater in *both* the lower and the upper parts than in the original granite. We must, therefore, add to the complex conditions pointed out above a contamination from the pot or furnace, at least from some outside source. Clearly no significance can be attached to the experiment in the matter of indicating the effect of gravity in producing composition differences in a liquid.

The rather rapid melting of a mixture of minerals such as a granite cannot be a simple process. It begins with the liquefaction of those substances which flux most readily together, not necessarily those of lowest melting-point. The substances first melted are principally those rich in alkaline earths and iron. The liquid, as gradually formed, tends to filter down through the porous material and collect toward the bottom. Thus there results in the early stages a relative concentration of alkalic and siliceous materials toward the top. The more siliceous and alkalic substances, which assume the liquid state with great reluctance, dissolve slowly, and in time all becomes liquid. The melt will, however, be layered as a result of the accumulation of the first-formed liquid at the bottom and possibly the floating of crystal grains buoyed up by

gas bubbles at a later stage. The persistence of this layering, or, better, continuous composition gradient, is due only to the inability of diffusion to overcome it in such viscous melts in any reasonable time. The phenomenon was noted long ago by Sorby. In describing the melting of Mount Sorrell "syenite," a hornblende granite, he says, "The hornblende melted more easily than the quartz and feldspar, and a portion of those minerals has risen upward."[1]

The phenomena which take place in the glass-maker's pot are essentially of the same general nature; that is, the difficulty connected with obtaining a homogeneous melt in glass practice is due to initial inhomogeneity and not to any tendency of the liquid, once homogeneous, to become inhomogeneous. The truth of this statement becomes obvious when it is realized that the glass-maker, in order to reduce inhomogeneity, resorts to long-continued heating, thereby affording diffusion sufficient time to accomplish the desired result. If there were any tendency to *become* inhomogeneous, continued heating would give precisely the opposite effect.

SEPARATION OF DISTINCT PHASES

The possibilities of composition differences that have been considered are those which may conceivably exist in a magma still entirely fluid and consisting of but one phase. They are not adequate to explain the differences actually observed in nature in the crystallized product of the magma. As soon, however, as new phases begin to separate from the magma, the possibility of obtaining composition differences in different parts is enormously increased, if there is any mechanism whereby a relative concentration of the new phase or phases in certain parts may be accomplished. The new phases might be either liquid or crystalline and the factors which might result in their concentration in certain parts are diffusion, convection, gravity, and earth movements. Consideration will first be given to the question whether the separation of liquid phases, i.e., immiscibility in the liquid state, is a factor in differentiation.

[1] *Proc. Geol. and Polytech. Soc. W. Yorkshire*, IV (1863), 302.

Liquid immiscibility in magmas.[1]—It is well known that many liquids which are quite homogeneous at high temperatures may separate at lower temperatures into two or more non-consolute liquid fractions, and the hypothesis that igneous magmas form such immiscible fractions is favored by some investigators. Often it seems not to be realized that the formation of an immiscible liquid fraction is not in itself sufficient for differentiation. There must be some mechanism for the relative concentration of the immiscible liquid in certain parts, and those who deny the efficacy of, say, gravity in the production of a local concentration of certain crystalline phases must, logically, do the same for immiscible liquid phases.

Vogt has made a study of the question of liquid immiscibility in silicates, considering both experimental and field evidence, and has arrived at the conclusion that the rock-forming silicates are freely miscible in all proportions. For certain minerals like the sulphides, he concedes partial immiscibility.[2]

Some geologists are inclined to disagree. Daly, for example, in speaking of the complete miscibility of liquid silicates, says: "It may be quite true for high temperatures and yet quite untrue for a temperature just above that of crystallization of a given component. No one has yet succeeded in holding a molten mixture of silicates within this narrow range of temperature for a length of time sufficient to warrant any conclusion on the matter."[3] On the contrary, in the great number of quenching experiments which have been made at the Geophysical Laboratory on a rather compre-

[1] The term "liquation" is now quite commonly used in petrologic literature to designate the act of separation into immiscible liquid fractions. This modern usage has probably been the cause of the insertion of this meaning in the supplement to the *Century Dictionary*. Schweig appears to apply it, however, to the process of separation of liquid from crystals which he contrasts with separations of any kind in the liquid, a contrast always to be carefully borne in mind in any discussion of differentiation. Schweig's usage appears to be the more justifiable on the basis of the borrowing of the term from the metal-worker, to whom it indicates a process of separation of a liquid portion from a crystalline or solid portion such as that accomplished in the Pattinson process for the purification of silver. However this may be, the writer considers it advisable to avoid the term, since, without its context, it does not convey a definite meaning especially with regard to the very much contrasted processes mentioned above.

[2] *Silikatschmelzlösungen*, I, 96; II, 228.

[3] Daly, *Igneous Rocks and Their Origin*, p. 226.

hensive variety of silicate mixtures, ideal conditions are maintained for the discovery of liquid immiscibility. The charges are held at various temperatures, both above the temperature of beginning of crystallization and throughout its range, for a period of time sufficient to obtain equilibrium between the liquid phase and the crystalline phases. How much more readily would equilibrium have been obtained between two liquid phases if there had been any tendency toward the formation of two such phases! Yet not a single instance of liquid immiscibility has been encountered in the whole course of this work. The experiments have been conducted both at atmospheric pressure and in some cases in bombs under high pressure of water-vapor.

It may be pointed out that, for the detection of immiscibility, it would not have been necessary to allow sufficient time for the collection of the immiscible portions into separate layers. The separation of globules of liquid 0.01 mm. in diameter and even much smaller could not have escaped detection during the microscopic examination of the quenched products. Continued experimental work is, then, in accord with Vogt's conclusion, and it is safe to repeat that the experimental evidence, as far as it goes, is decidedly against liquid immiscibility.

In the case of natural rocks, differences of composition in various parts of a body, when completely crystalline, might be referred equally well to the separation either of crystalline or of liquid phases. Similarly, there is no compelling reason for preferring liquid immiscibility as the explanation of the association, however intimate, of *distinct* lava flows of different composition, such as the basaltic and rhyolitic lavas of Iceland. Granting that both came from the same source, it is possible that the extrusion of the different varieties was separated by periods of years, during which interval there was plenty of opportunity for a change in the composition of the liquid in the magma basin due to the separation of crystals from it.

Even the cases, sometimes described, of simultaneous intrusion or extrusion at the same locality of different magmas does not prove their coexistence as *immiscible liquids* in the same pool. There is often, on the contrary, distinct evidence, when two magmas are

brought together in this manner, that they have a strong disposition to mix and do so to the extent of their ability before crystallization or cooling to the glassy state ensues. The facts point rather to derivation of these magmas in most cases from separate, though adjacent, pools, say, laccolithic chambers.[1] The pools may originally have contained the same magma, but on account of a difference in size and consequently in rate of cooling were, at the time of reintrusion, at different stages in their career of crystallization and therefore, as will be shown in the sequel, the still liquid portion drained-off from the one had a different composition from that drained from the other.

There is only one kind of phenomenon which could be considered as definite proof of the occurrence of limited liquid miscibility and it would, without doubt, be very commonly observed if limited miscibility among rock-forming silicates were a fact. The observed phenomenon would be the occurrence in glassy, or partly glassy, extrusive lavas of distinct globules of material still partly glass, large or small according to their opportunity for aggregation, and of composition different from that of the main mass. Here would lie indisputable proof of the formation of immiscible liquid globules. So far as the writer is aware, no such case has been described, in spite of the fact that lavas, as a group, depict all igneous processes arrested, more or less successfully, at all possible stages. They are Nature's quenching experiments.

The rare globular masses found in those completely crystalline plutonic rocks to which the term orbicular has been applied are an entirely different matter. It is often demonstrable that these owe their origin to the localization of *crystallization* of certain constituents, due to the cooling and chemical effect of a foreign inclusion, the remains of which often constitute the nucleus of the orbule.[2] The occurrence of such structures as an exceedingly rare curiosity shows that they always require special conditions and are not a normal result of cooling as the formation of immiscible

[1] Certain stages of crystallization at which the liquid portion may have different compositions in different parts of a single reservoir will be discussed later.

[2] Von Chrustschoff lists other possibilities (*Mém. Acad. Sci. St. Pétersbourg* [7], XLII, No. 3).

liquid portions should be. If they are ever due to a separation in the liquid state, it is remarkable that sudden extrusion has not happened to give plain evidence of the fact in the occurrence of similar orbules of *undercooled liquid* in the extrusive types. In the absence of evidence of this kind, it is necessary to reject liquid immiscibility as a factor in the differentiation of igneous rocks. Lavas could not fail to show the separation of liquid phases in all its stages just as clearly as they do the separation of crystalline phases in all its stages. Attention must be directed toward the separation of crystalline phases—i.e., crystallization—as the fundamental factor in differentiation though the possibility that sulphides and perhaps some oxides may become immiscible under certain conditions may be freely admitted. It may be pointed out that, considered on general grounds, limited miscibility between such dissimilar substances as sulphides and silicates is likely, but wholly unlikely among the silicates themselves, substances which have such remarkable tendencies to be miscible even in the solid state.

Differentiation through crystallization.—Differentiation may be brought about as a result of crystallization in two ways: through the localization of crystallization and through the local collection of crystals.

Since the outer parts of a body of magma are always cooler than the interior, there is a certain period during which crystallization is taking place only near the border, the interior being still above the temperature of beginning of crystallization. It has been supposed that during this period precipitation of the mineral or minerals of early crystallization takes place in the cooler parts, but that this does not bring about a local impoverishment of the liquid in the crystallizing material, the composition of the liquid being kept uniform and continued growth of the crystals being maintained by free diffusion from all parts of the liquid[1] or by convection currents.[2] Thus there results a general richness of the border phase in minerals of early crystallization, according to this belief. Such freedom of diffusion Becker has shown to be altogether inconsistent with what is known on that subject. Apart

[1] A. Harker, *The Natural History of Igneous Rocks*, p. 318.

[2] G. F. Becker, *Am. Jour. Sci.* (3), 1897, pp. 21–40.

from this the rocks themselves show that diffusion is quite limited in its scope. When centers of crystallization are once established at the border, diffusion as free as that postulated should lead only to the continued growth of the crystals so initiated. There is no reason why new centers should be established. The result should be the growth inward from the contact of huge crystals of the minerals of early separation. In reality, of course, a new center of crystallization for these minerals is always established within a few millimeters, a fact which speaks eloquently for the radius through which diffusion acts freely.

The same objections apply to the supposed maintenance of approximate uniformity in the composition of the liquid through the agency of convection currents, or, better stated, perhaps, the continual supply of new liquid to the border portion. The same huge crystals at the border should result.

Let us suppose, however, that, in some accidental manner, say, before convection has fairly started, many centers of crystallization of these early minerals are established near the border. If these centers were fed by convection currents coming from distant parts of the magma, none of the crystals except those actually attached to the wall rock would remain in the border portion. They would be carried away and distributed by the same currents that are supposed to feed their growth. If the numerous early crystals established near the border are supposed to grow by diffusion of material from a distance, there is a similar difficulty. Such a process would require a long period of time and there is no reason to believe that the crystals would remain there when the border concerned is, say, the upper margin of a sill. The crystals would in this case sink out of the border portion.[1]

[1] Experimental work forbids the belief that diffusion could take place freely *through considerable distances* in a period of time too brief to permit significant sinking of crystals (cf. Harker, *op. cit.*, p. 322). For example, a liquid consisting of 56 per cent $CaMgSi_2O_6$ and 44 per cent $MgSiO_3$ permits quite definite effects in the way of sinking crystals at 1430° in only 15 minutes, but if one tries to make the foregoing liquid by carelessly mixing diopside and $MgSiO_3$ and holding the mixture at a temperature considerably above 1430°, little headway toward a homogeneous melt will be made in 15 minutes. The materials must be very carefully mixed in the form of a fine powder (N. L. Bowen, *Am. Jour. Sci.* [4], XXXIX [1915], 176).

If either free diffusion or convection toward the cool boundary were the effective agent in producing the concentration in that region of the minerals of early crystallization, we should expect large crystals of these minerals attached directly to the wall rock, or if the crystals were of small size they should be attached to each other and ultimately to the wall rock. In nearly all cases these early minerals occur, on the contrary, in small discrete crystals separated from each other by crystals of later formation which must have been a part of the liquid magma at the time the supposed diffusive or convective processes were taking place. At this time, then, they could not have been attached either directly or indirectly to the wall rock and there is no reason why they should have remained in the border position.

For the reasons above outlined, the processes of diffusion or convection during crystallization cannot in general be considered satisfactory explanations of "basic border phases." Diffusion toward the cold boundary prior to crystallization, the Soret action, has also been found wanting. Daly[1] has offered an explanation of basic border phases which seems to be entirely satisfactory in most cases. He pictures the border phase as a quickly chilled portion having the composition of the original magma and the more salic phase adjacent to it as the lighter differentiate formed during the slow cooling of the rest of the magma.[2] For stocks, batholiths, and large laccoliths, this process has distinct advantages over a process involving diffusion toward a chilled border. Daly has in this manner successfully explained that classic example of a body exhibiting a basic border, the Shonkin Sag laccolith.

In the case of small bodies like most dykes, it seems to the writer to be more commonly true, for those having basic border phases, that the dyke fissure serves as a channel for the passage of magma during a considerable period. As the chilled layer forming on the cold walls gradually increases in thickness, the composition of the magma passing through gradually becomes more acid on account of a like change in the composition of the magma in the

[1] Daly, *Igneous Rocks and Their Origin*, p. 244, Fig. 123, and p. 246, Fig. 126.

[2] In a later part of the paper the manner in which quick cooling prevents differentiation and slow cooling promotes it will be shown in detail.

feeding reservoir as crystallization proceeds. Some composite dykes at Cape Ann, on the Massachusetts coast, give distinct evidence of this process. These dykes are more salic in the central portion, and in places there is a continuous gradation in composition toward the more basic margin. Here the variation might be referred to differentiation in place, but that this conclusion would be erroneous is shown by the fact that in other places in the same dyke the more basic phase has been completely frozen, and only after a reopening of the dyke by fracture has the more salic phase entered. This refracturing has in some places been repeated. The evidence is clear that the dyke fissure has served for the passage, throughout a considerable period of time, of material of continually changing composition.

In general this explanation of basic borders when they are shown by small bodies such as narrow dykes or sills seems preferable to any process of differentiation in place.

The most promising processes for the production of differentiation are those involving crystallization and the relative movement of the crystals with respect to the liquid from which they separated. Of these the most important during the period when the magma is still dominantly liquid is the movement of crystals in the liquid on account of differences in density, usually the sinking of crystals. During the period when the magma has largely crystallized, "the straining-off or squeezing-out of the residual fluid magma"[1] is the most important process. It is to be noted, however, that in the strained-off, reintruded liquid from the latter process, the sinking of crystals may begin again, so that it is difficult to refer either of these processes to any definite period in the complete history of any given magma.

No one can reasonably question the existence or the effectiveness of a process of squeezing out of residual magma, but many have maintained that there is no evidence that crystals sink in magmas. Numerous examples, however, have now been described of sheetlike bodies with both roof and floor exposed and the differentiates arranged in such a way as to point clearly to the sinking of crystals. An antagonistic view is, therefore, no longer tenable. Those

[1] A. Harker, *op. cit.*, p. 323.

opposed to the process seem to expect too much of it, especially in the way of a sorting of the individual minerals. Thus it is stated that the iron ores do not accumulate at the bottom of the sill. This statement is not strictly true, for sometimes they do;[1] nevertheless such a phenomenon is to be expected only rarely. Let us assume the most favorable case. The separation of the ore minerals as the first products of crystallization takes place and their separation is complete before other crystals appear, a thoroughly unlikely assumption. The period of crystallization of the ore minerals *alone* would be even in this case exceedingly brief for bodies of moderate dimensions, and such are most bodies whose floors are visible. It is to be noted, moreover, that the very heavy minerals usually occur as relatively small crystals and the size of crystals is a factor of prime importance in determining their rate of sinking. Very small crystals of magnetite would, as a rule, make little headway before crystals of other minerals were precipitated.[2] Throughout most of the period of crystallization of the magma the ore minerals are merely one of a number of kinds of crystals and their sinking is seriously interfered with by the presence of other crystals which may tend to sink much more slowly or in rare cases perhaps even to float. In general, we must conclude that there may be a long period in the history of a crystallizing magma during which the crystals tend to sink through the liquid as a swarm, with little tendency to relative movement between the different kinds of crystals, the sinking being determined rather by the mean density of the swarm. The result of this process is, in general, not the sorting of individual minerals, but the downward movement of the heavier minerals of early crystallization as a group and the contrasting of the minerals of the basic rocks with those of the intermediate rocks and with those of the acid rocks.

[1] The lower part of the Duluth gabbro is in places 90 per cent titaniferous magnetite (Bayley, *Jour. Geol.*, II [1894], 818). Foslie recently described a Norwegian example (*Norges. Geol. Unders. Aarbok* IV [1913], 66), and many others could be cited.

[2] Assuming the densities of magnetite and orthoclase, for example, to have roughly the same relative values at high temperatures as at low temperatures, we may deduce that magnetite crystals 0.1 mm. in diameter would sink in most granitic magmas no faster than feldspar crystals 0.4 mm. in diameter.

As the more specific descriptions given later will show, sills and laccoliths of basic magma very commonly give evidence of this process when of sufficient thickness, which apparently must, as a rule, be as much as 500 to 1,000 feet or more. Much thinner sills sometimes show it[1] and much thicker sills often fail to show it, but this is nothing more than is to be expected. A small sill which is one of a large number intruded at approximately the same time into the beds of a sedimentary series will cool more slowly than a sill of equal size which is practically alone in such a series. Many thick basic sills or laccoliths are possibly not the result of instantaneous intrusion, the spreading apart of the strata being slowly accomplished so that the thickness of the sill may not have been increased much faster than the thickness of the layers of frozen magma formed on roof and floor. In such a case no differentiation of the type referred to is to be expected. Repeated violent shocks, localized escape of gases, or anything which might cause a streaming of the liquid magma may also be expected to prevent differentiation. Finally, bodies of great size in which this type of differentiation has occurred are especially liable, because of their slow crystallization, to be still partly liquid at a time of important later disturbances, and these are likely to obscure the simple density arrangement of differentiates and especially to obliterate the evidences of gradual transition of one type into another. Thus tongues of the still liquid portion may be injected into fissures and cracks formed in the crystallized portion and give the impression of having arrived as the result of a separate and distinct principal act of intrusion when really a product of differentiation practically in place.

Important effects due to the sinking of crystals are hardly to be expected in *sills* of salic magma. Such magma depends for its fluidity on its ability to retain volatile constituents, whereas the basic magmas are comparatively fluid in virtue of the nature of the silicates themselves. The intrusion of a salic magma as a sill-like body, exposing a great total surface in more or less porous rocks, favors the escape of much of its volatile material. The

[1] The very clear example of sinking of pyroxene crystals in a sill only 30 feet thick described by Iddings from Yellowstone Park must be regarded as a very exceptional case (*U.S. Geol. Survey, Mon. XXXII*, Part 2 [1889], pp. 82–84.)

resulting great viscosity may be reasonably expected to prevent important sinking of crystals.[1] Nevertheless the sinking of crystals may be of considerable importance in a very large body of salic magma which exposes to the surrounding rocks a minimum of surface in proportion to its mass.

The two processes involving relative movement of crystals and liquid—the sinking of crystals and the squeezing out of residual liquid—aid each other in a general way in the production of an arrangement of the various differentiates, such that the heaviest lies at the greatest depth, and the lighter ones at lesser depth—a gravitative adjustment.

Daly has collected from the literature and from personal study a host of instances illustrating quite convincingly the fact of gravitative adjustment.[2] The two processes mentioned above are, the writer believes, the sole instruments of its production. On a later page a discussion will be given of the working of the processes in specific cases.

The formation of zoned crystals is a process which may well be discussed at the same time. It is somewhat related to the two processes mentioned above, inasmuch as the zoning of a crystal effectively separates the earlier-formed part of the crystal from the neighboring liquid in which it formed. This fact has an important effect on crystallization and therefore on differentiation.

THE ASSOCIATION OF DIABASE AND MICROPEGMATITE

Diabases with micropegmatite interstices are very common. Sometimes the micropegmatite (granophyre) is separated as a distinct body, a granite, granodiorite, or quartz diorite in composition. This association is of fundamental importance to petrogenic theory and will be made the starting-point for a discussion of the geologic evidence supporting crystallization differentiation. It is, in many cases, clearly shown that when the diabasic (basaltic) magma was intruded as a small body and was therefore quickly

[1] In pegmatite sheets in California in which, no doubt, fluidity was maintained, Schaller has found very striking examples of the sinking of garnet crystals (personal communication from Dr. Schaller).

[2] *Op. cit.*, pp. 228 f.

chilled, it crystallized as a normal plagioclase-pyroxene diabase without quartz. On the other hand, large bodies usually show micropegmatitic interstices and often a similar salic differentiate. This contrast between the larger and the smaller bodies has led some petrologists to the opinion that the more slowly cooled, large bodies had an opportunity denied the quickly cooled bodies—the opportunity to assimilate siliceous material, whence the siliceous differentiate. Direct evidence of adequate assimilation is seldom if ever clear; its accomplishment is nearly always inferred from the existence of the acid differentiate. In the following an attempt will be made to show that the distinction often noted between the large and small bodies is solely the result of a difference in the course of crystallization dependent upon the difference in the rate of cooling. The plan will be to discuss the physical chemistry of the crystallization of investigated systems which have a direct bearing on the question and then to apply the facts and principles developed to the crystallization of basaltic magma. It may seem, perhaps, that a discussion in which physical chemistry plays so prominent a part has no place in a geological paper, but it is in reality one of the many phases of that subject which the petrologist must master if a foundation is desired on which a discussion of the crystallization of igneous magmas may be based.

THE SYSTEM DIOPSIDE-FORSTERITE-SILICA

In a recent paper the writer has published an investigation of the system diopside-forsterite-silica, in which the comparative effects of slow and of quick cooling were discussed on the basis of definite experimental results. The discussion has sufficient importance in the present connection to warrant its partial repetition here. For fuller details the original paper may be consulted.[1]

Fig. 1 is an ordinary ternary composition diagram, composition being plotted on triangular co-ordinates. Any point within the triangle represents a definite composition, definite relative proportions of the three components. The area of the triangle is divided into four *fields* by the *boundary curves*, *BFA*, etc. The field of forsterite is such that it contains all the points representing

[1] *Am. Jour. Sci.* (4), XXXVIII (1914), 207.

the composition of all the liquids which can exist in equilibrium with (are saturated with) crystals of forsterite. Similarly the field of the pyroxenes contains the composition of all the liquids which can exist in equilibrium with (are saturated with) crystals of pyroxene, the composition of the pyroxenes themselves being represented by points lying along the *conjugation line* (dotted line joining $MgSiO_3$ and diopside, between which there is an unbroken series of pyroxene mix-crystals). Any liquid whose composition is represented by a point lying on a boundary curve is in equilibrium with (saturated with) two kinds of crystals, and any liquid whose composition is represented by the point at which three boundary curves meet is saturated with three kinds of crystals. There is only one such liquid in the present system, that in equilibrium with pyroxene, tridymite, and cristobalite. Fig. 1 is therefore a *solubility diagram*.

By drawing isotherms on the figure any point can be made to represent (besides a definite composition) a definite temperature. In Fig. 1 the direction of falling temperature is merely indicated by arrows on the boundary curves, but in Fig. 2 the experimentally determined isotherms or temperature contour-lines are shown. In Fig. 2 any point within the forsterite field represents, not only the composition of a liquid saturated with forsterite, but also the temperature at which the liquid becomes just saturated with forsterite and its crystallization begins. This is also, of course, the temperature at which melting is complete, and Fig. 2 is therefore, besides a solubility diagram, a *melting-point diagram*. It is more common to refer to such diagrams as melting-point diagrams, emphasis being placed on the temperature aspect, but in complicated systems it would, for many purposes, be better to emphasize the composition aspect, solubility being the principal consideration, as will appear later in the consideration of the crystallization of magmas.

Fig. 3 is analogous to Fig. 1, showing the boundary curves somewhat displaced in order to lessen the confusion of lines and facilitate the discussion. Isotherms are omitted, but it must be considered that any point represents both a definite composition and a definite temperature.

Crystallization with perfect equilibrium.—Crystallization of a liquid of composition M (Fig. 3) takes place in the following manner *when perfect equilibrium prevails*. At the temperature of the point M the liquid becomes saturated with olivine (forsterite), and crystals of that substance begin to separate. The composition of the liquid then changes along the line AMK toward K with continued separation of forsterite. When the temperature of the point K is

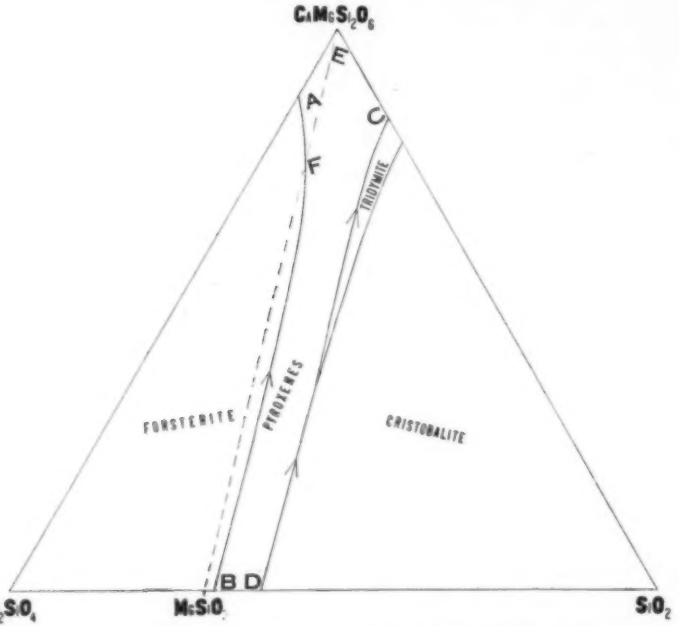

FIG. 1.—Field diagram of the system: diopside, forsterite, silica

reached, the liquid becomes saturated with pyroxene, and pyroxene of composition L begins to separate, i.e., pyroxene rich in magnesia. At the same time forsterite begins to redissolve and the composition of the liquid begins to change along the boundary curve from K toward N. Meantime the composition of the pyroxene separating, as well as that of the pyroxene which has already separated, changes from L toward P (becomes more calcic). When the temperature of

the point N is reached, the last of the liquid disappears, the vanishing quantity having the composition N, and the pyroxene having the composition P. The whole then consists of pyroxene of composition P and forsterite in the proportions pyroxene: forsterite = $MA:MP$.

If the composition of the original liquid had been that of the point P, the separation of forsterite would begin at the temperature

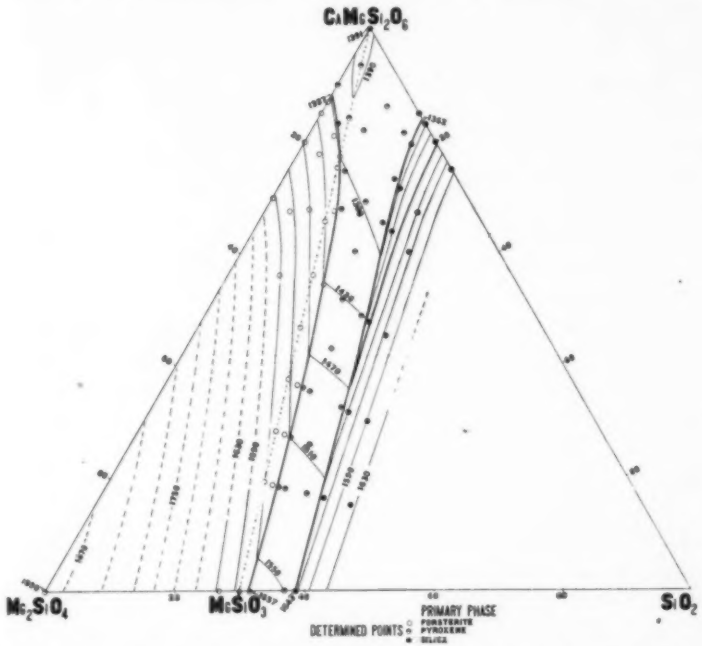

FIG. 2.—Temperature-composition diagram of the system: diopside, forsterite, silica

of the point P, and the course of crystallization would be the same as in the foregoing case except that at the temperature of the point N the last of the forsterite is redissolved and the last of the liquid is used up at the same instant and the whole consists of pyroxene of composition P. Thus all mixtures of forsterite with pyroxene P, or pyroxene P itself (i.e., any composition represented

by a point on the line AP) become completely crystalline at the temperature of the point N, the last minute quantity of liquid having the composition N. A mixture of pyroxene L with forsterite (i.e., any composition lying on the join AL) would, however, become completely crystalline at the higher temperature K, and the last minute quantity of liquid would have the composition K. A mixture of pyroxene T with forsterite (i.e., any composition lying

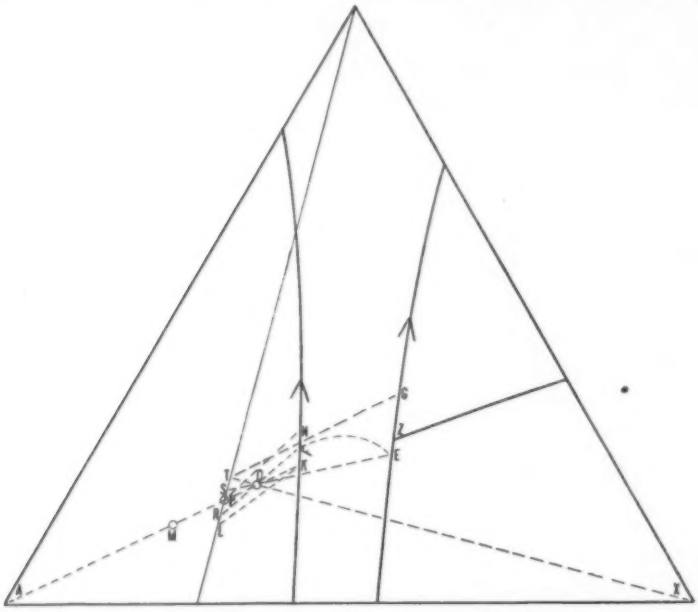

FIG. 3.—Crystallization curves for the system: diopside, forsterite, silica

on the join AT) would become completely crystalline at a temperature lower than N, and the last of the liquid would be more calcic than N.

Thus any mixture represented by a point on any line passing through A has a temperature of final crystallization different from that of a mixture lying on any other line through A, and the composition of the final liquid is different in each case. There is, moreover, in each case a continual change in the composition of the

liquid as the temperature falls, until the last drop is used up, and a concomitant change in the composition of the mix-crystals. Contrast such crystallization with the crystallization in a simple eutectic system, which is sometimes regarded as throwing light on the crystallization of igneous rocks. In the eutectic system, in all possible mixtures, the composition of the liquid continually approaches that of the eutectic mixture, and when it attains this composition there is no further change and no change in temperature until all is crystalline. The temperature of final crystallization is the same for all mixtures. The difference between these two types of systems is due principally to the existence of a mix-crystal series in the one and its absence in the other. Through consideration of eutectic systems, little aid is to be obtained toward the understanding of the crystallization of igneous rocks, in which mix-crystals are so common.

If the composition of the original liquid was that of the point *D*, forsterite would crystallize first as before and crystallization would follow the same course as in the two preceding cases (*M* and *P*) until the temperature of the point *F* is reached. At this temperature the re-solution of forsterite is complete and the mixture consists of liquid of composition *F* and pyroxene of composition *R*. The composition of the liquid now leaves the boundary curve and crosses the pyroxene field on the curve *FE*, pyroxene continuing to crystallize and changing in composition toward *S*. When the temperature of the point *E* is reached, cristobalite begins to crystallize. At this temperature the liquid has the composition *E* and pyroxene the composition *S*. With further lowering of temperature the composition of the liquid changes along the boundary curve from *E* toward *Z*, cristobalite and pyroxene continue to crystallize, and the pyroxene changes in composition toward *T*. At the temperature of the point *Z*, cristobalite changes to tridymite, and with further lowering of temperature tridymite and pyroxene continue to crystallize. When the temperature of the point *G* is reached, the liquid finally disappears; the last minute quantity has the composition *G* and the pyroxene has the composition *T*. The whole now consists of pyroxene of composition *T* and tridymite in the proportion pyroxene : tridymite = *DX* : *DT*.

Crystallization with zoning.—It has been stated that crystallization takes place after the manner described for the foregoing mixtures when perfect equilibrium is obtained. The early crystals of forsterite must be partly or completely redissolved and the crystals of pyroxene must, by diffusion in the solid, continually change composition throughout their entire mass. This result could be accomplished only with extremely slow cooling and with continuous mixing to prevent the sinking of crystals. With quicker cooling an entirely different result will be obtained.

If the cooling is at such a rate that forsterite crystals are not redissolved and pyroxene crystals once separated do not change their composition, then from *any of the liquids M, P, or D* of Fig. 3 forsterite would separate first as before until the temperature of the point *K* was reached, when the liquid has the composition *K*. At this temperature pyroxene of composition *L* begins to separate as before, but re-solution of forsterite does not take place in this case. The composition of the liquid therefore does not follow the boundary curve but crosses the pyroxene field and meets the boundary curve pyroxene-tridymite at a point lower than *E*, say *G*. In the meantime the composition of the pyroxene separating has changed from *L* to *T*, and the pyroxene crystals therefore show zones of continuous change of composition varying from *L* to *T*. When the temperature has reached that of the point *G* and the composition of the liquid is *G*, tridymite begins to crystallize and the composition of the liquid changes along the boundary curve pyroxene-tridymite. Meantime the composition of the pyroxene separating changes from *T* toward pure diopside, and final crystallization takes place only when the temperature is that of the eutectic diopside-tridymite, when the remaining infinitesimal amount of liquid has the composition of this eutectic and the crystalline phases separating are tridymite and pure diopside.

Any of the liquids *M*, *P*, or *D* will, then, if crystallized in this manner, consist of forsterite, tridymite, and pyroxene varying in composition from *L* to pure diopside. The actual amount of pyroxene approaching *L* in composition is relatively large; the amount approaching diopside, relatively small; the amount of pure diopside, infinitesimal. The kind of crystallization which

results in the foregoing case will be referred to in the following as *maximal zoning*.

If the cooling is extremely rapid, the mixture *M* may undercool to some temperature below *N* before crystallization begins, when it will crystallize to a mixture of forsterite and pyroxene *P*. It has already been shown that extremely slow cooling (with mixing) will give the same final product, no zoning of the crystals resulting in either case. There is one definite intermediate rate of cooling which will give maximal zoning. If the cooling is somewhat slower than the definite rate which gives maximal zoning, there will be opportunity for partial change in the composition of the various zones, and the mixture *D*, for example, instead of becoming completely crystalline only at the temperature of the eutectic diopside-silica, will be completely crystalline at a somewhat higher temperature, and the outer zone of the mix-crystals, instead of being pure diopside, will be somewhat more magnesian. If the cooling is somewhat faster than the rate which gives maximal zoning, the same result will be accomplished, this time because of slight undercooling maintained throughout crystallization. Any intermediate rate of cooling differing from the rate which gives maximal zoning will, therefore, give some zoning, but with a smaller range of composition between the inner and outer zones, this being accompanied by a smaller range of temperature of crystallization and a smaller range in the progressive change in the composition of the liquid than that shown in maximal zoning. It is obvious that the rate of cooling has a fundamental effect on the course of crystallization in the mixtures of the system investigated and indeed must have a similar effect on the crystallization of any mixtures from which mix-crystals separate.

Crystallization when the crystals are free to sink in the liquid.—Even when the cooling is extremely slow, approaching or even realizing the rate required to produce perfect equilibrium, the sinking of crystals is a factor entering into the problem and tending to produce the same general result as the intermediate rates of cooling which give rise to zoning. The continual downward movement of growing crystals accomplishes their removal from that part of the liquid from which they crystallized. The effect

on the liquid is similar to that produced by zoning, for zoning accomplishes a cutting off of an early crystal from the liquid by the formation of a zone of different composition about it.

A mass of liquid of composition *M* is cooled uniformly in all parts and forsterite crystals are imagined to sink from the upper to the lower layers. When the temperature *K* is reached, the liquid has the composition *K* in all parts, but it holds only a few olivine (forsterite) crystals in its upper layers and many in its lower layers.[1] The total composition of a certain upper layer could, then, be represented by the point *D*, and of a certain lower layer by some point between *M* and *A*. Imagine, for simplicity, that further sinking of crystals is prevented; then, as the temperature falls below *K* the separation of pyroxene and the re-solution of forsterite proceed in all layers. When the temperature *F* is reached, the solution of forsterite is complete in the upper layer of composition *D*, but is still incomplete in the lower layer. With further cooling, re-solution of forsterite continues in the lower layer until at the temperature *N* all the liquid is used up. *The lower layer is now completely crystalline*, consisting of a mixture of pyroxene *P* and forsterite, *but the upper layer is still partly liquid*, for, in the meantime, the composition of liquid in this layer has crossed the pyroxene field on the curve *FE* and the liquid is not entirely used up until the temperature *G*, much lower than *N*, is reached. When the temperature *G* is reached, the upper layer then consists of pyroxene of composition *T* and tridymite. There is, therefore, not merely a marked difference in composition between the lower and the upper parts of the crystalline product, but also *a partly different assemblage of minerals*.

It is important to note that as the temperature falls below that of the point *F* the composition of the liquid portion, which up to this point has been uniform from top to bottom, now pursues a different course in the upper layers from that followed in the lower layers. At a temperature a few degrees below *F* the composition of the liquid in the lower layers is represented by a point between *F*

[1] This sinking of olivine crystals is not an imaginary process but has been obtained in crucibles containing these melts (N. L. Bowen, *Am. Jour. Sci.* [4], XXXIX [1915], 175).

and *N* and that in the upper layers by a point on the curve *FE*. A squeezing out of the liquid from such a mass might bring these different liquids together and draw them out into streaks which though perfectly miscible would have only a limited opportunity to mix before crystallizing, and would thus give a result simulating primary banding, a rather rare but quite definite phenomenon of igneous rocks.

It has been supposed in the foregoing that only crystals of forsterite settle out, but it may readily be imagined that in a certain limited portion nearly all the forsterite has settled out at the time when the crystallization of pyroxene begins and that there is opportunity for the sinking of pyroxene crystals. Even in layers having an abundance of forsterite crystals, pyroxenes will crystallize and join the sinking swarm. The result is an enrichment of the lower layers in the more magnesian pyroxenes of early separation with a consequent *raising* of their temperature of final consolidation somewhat above *N*, whereas the liquid in the upper portion is continually enriched in more calcic pyroxene with a consequent *lowering* of its temperature of final consolidation below *G*. The composition of the liquid is, in fact, continually *offset* toward the eutectic diopside-silica. In an ideal case the composition of the last minute quantity of liquid would reach the eutectic diopside-silica, but in any actual case the eutectic will not be attained, the last of the liquid being used up before the temperature and composition of the eutectic is reached. The temperature of final consolidation of the residual liquid and its composition will lie at some point intermediate between *G* and the eutectic diopside-silica, approaching closer to the latter according as the opportunity for the sinking of crystals increases. The opportunity for the sinking of crystals is directly related to the rate of cooling. It is obvious, therefore, that the rate of cooling is of fundamental significance in controlling the ultimate products of crystallization.

In a system with simple eutectic relations, settling of crystals could make no difference in the temperature of final consolidation of the last of the liquid, nor in its composition.

Crystallization with straining off of the liquid.—A process involving the separation of crystals and liquid by the squeezing out of

residual liquid will evidently work in the same direction as the two processes of zoning and sinking of crystals, but it differs in not having the same continuous nature, being rather an incident in the history of the magma, though, no doubt, repeated several times in some cases.

THE SYSTEM ANORTHITE-FORSTERITE-SILICA

After discussing the crystallization of liquids of the foregoing system involving an olivine, a series of pyroxenes and silica, a system involving a feldspar, an olivine, a single pyroxene, and silica will now be considered. This is the system anorthite-forsterite-silica recently investigated by Andersen.[1]

The equilibrium diagram is shown in Fig. 4.

Crystallization of liquid of composition x, a mixture of clino-enstatite and anorthite, may take place in any of the following ways. With perfect equilibrium and sinking of crystals prevented, forsterite separates first and the composition of the liquid changes along the line xy. At the temperature y the pyroxene clino-enstatite begins to separate and forsterite to redissolve, the liquid changing in composition along the boundary curve FM. When the temperature M is reached, the last of the liquid (composition M) and the last of the forsterite disappear and the whole consists of the pyroxene, clino-enstatite, and anorthite. The same final result would be obtained if the liquid were cooled very rapidly, that is, if considerable undercooling occurred.

If, however, forsterite crystals settled from the upper to the lower layers, the consequence would be that at the temperature M the liquid would be used up in the lower layers before all the forsterite was redissolved and the whole lower portion would be crystalline, consisting of the *olivine, forsterite, the pyroxene, clino-enstatite, and anorthite*. The earlier crystals of olivine might collect in a separate layer, peridotite-like in nature. In the upper layers, however, the little forsterite remaining is redissolved while some liquid of composition M still remains and, after complete solution of forsterite, the liquid changes in composition along MN, clino-enstatite and anorthite separating until at the temperature N

[1] Olaf Andersen, *Am. Jour. Sci.* (4), XXXIX (1915), 407.

tridymite also separates and the whole crystallizes to a mixture of *the pyroxene, clino-enstatite, anorthite, and silica.* Thus the sinking of crystals has brought about a partly different assemblage of minerals in the upper and lower layers, a difference in temperature of final consolidation and in the composition of the final liquid of these layers. It is evident that even if the cooling were too

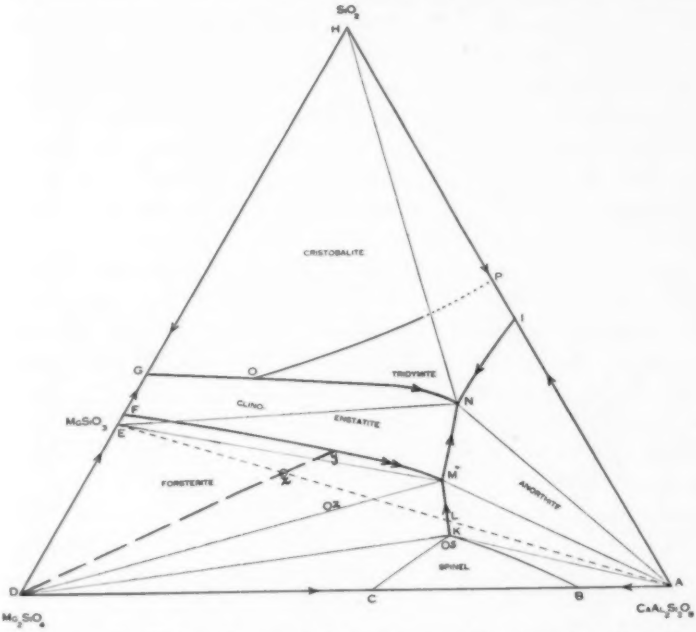

FIG. 4.—Equilibrium diagram of the system: anorthite, forsterite, silica, after Andersen, *Am. Jour. Sci.* (4), XXXIX (1915), 437.

quick to permit of any considerable sinking of crystals, the same consequence to the composition of the final liquid would result from the formation of a reaction rim of clino-enstatite about the forsterite crystals and their protection thereby from further resorption by the liquid.

If the composition of the original liquid were that of the point *z*, crystallization of the perfect equilibrium type and also crystallization

as a result of very rapid cooling would give a mixture of forsterite, clino-enstatite, and anorthite. Sinking of crystals would have the same result as in the case of the liquid x, but the total amount of forsterite formed would be greater and a considerable peridotite-like layer might be formed. If the composition of the liquid were that of the point s, slow crystallization with perfect equilibrium and no sinking of crystals and also very rapid cooling would give a final product of forsterite, clino-enstatite, and anorthite rather rich in forsterite but entirely free from spinel. Slow crystallization with sinking of crystals would remove the early-formed spinel crystals from that part of the liquid in which they formed and thereby prevent the re-solution which takes place with perfect equilibrium. These spinel crystals, collecting with the earlier forsterite crystals, would give a mass simulating a *spinel-bearing peridotite*.

It is to be noted that during the crystallization of the liquid x in which complete re-solution of olivine takes place with perfect equilibrium, there is a stage at which olivine crystals constitute about *15 per cent of the whole mass*. In case forsterite crystals sank during the crystallization of this mixture, the liquid would be of the same composition in all parts until the temperature y was reached, after which the liquid in the part containing olivine crystals would change in composition in a different manner from the parts of the liquid free from olivine crystals. The latter would depart from the boundary curve FM, cross the clino-enstatite field, and become completely crystalline when the temperature N was reached. The former would follow the boundary curve and become completely crystalline at the higher temperature M. During the period when the liquid in contiguous parts was forced to follow different courses by the presence of olivine crystals in the one part and their absence in the other, it seems likely that a squeezing out of the liquid might give rise to phenomena similar to those noted in the rather rare natural case of the intrusion of a heterogeneous magma—might, in fact, give a product simulating a banded gabbro. The liquids concerned would not, however, be immiscible.

It may be pointed out also that certain layers into which considerable olivine had settled would be peridotitic (lherzolitic) in

total composition (liquid and crystals) and at the same time would for a considerable period contain nearly or quite 50 per cent liquid. With such a proportion of liquid it would be eruptible as a whole and might be injected as dykes of peridotite into adjacent rocks, if we imagine these simplified magmas occurring in the crust of the earth. The eruptibility of this mixture would be increased by the fact that the injection must take place from a position of higher to one of lower pressure and, as a result of the lowering of pressure, re-solution of some crystals would take place. It appears likely, however, that this re-solution must be considered on the whole of relatively small importance and merely as aiding somewhat in the eruption of parts of a magma enriched in sunken crystals. We know little about the volume-changes and heat-effects involved in the solution of silicates in silicate liquids, but such indications as are to be gained from the same factors for the melting of single silicates suggest that the effect of relief of pressure in bringing about re-solution would be moderate. The great importance of this process assumed by Schweig[1] is unlikely. It appears also to be unnecessary to make this assumption in order to explain the facts for which it was proposed.

An increase in the eruptibility of a part enriched in sunken crystals through re-solution of the crystals in the hotter liquid appears to be also of limited importance. The factors limiting this action will be discussed on a later page.

CRYSTALLIZATION IN SYSTEMS INVOLVING THE PLAGIOCLASES

In natural rocks the plagioclases are a very important mix-crystal series. We shall now consider a system related to both those already discussed, involving the single pyroxene diopside, and the plagioclase mix-crystal series instead of the single plagioclase anorthite.[2]

CRYSTALLIZATION OF THE PLAGIOCLASES IN THE BINARY SYSTEM

Experimental work has confirmed the opinion that the plagioclases belong to Type I of Roozeboom's classification of mix-crystal

[1] *Neues Jahrb.*, Beil. Band XVII (1903), 563.

[2] N. L. Bowen, "The Crystallization of Haplobasaltic, Haplodioritic and Related Magmas," *Am. Jour. Sci.* (4), XL (1915), 161.

series.[1] It has also been possible to determine accurately the position of both solidus and liquidus so that the exact composition of solid and liquid in equilibrium with each other in the binary system is known[2] (see Fig. 5). The results, given in the paper referred to, show that the liquids are always very much richer in albite than

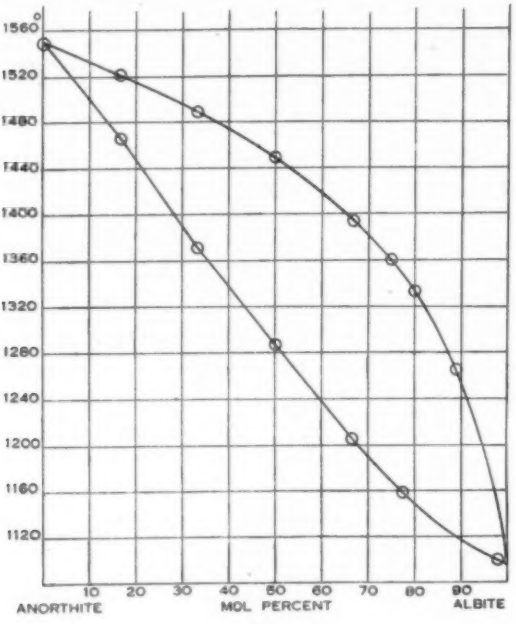

FIG. 5

the crystals with which they are in equilibrium. In discussing the crystallization of a liquid the consequences of zoning or the sinking of crystals were pointed out.[3] On account of the great viscosity of their liquids and consequent ease of undercooling, the artificial plagioclases prepared did not exhibit zoning, being different in this

[1] Day and Allen, "The Isomorphism and Thermal Properties of the Feldspars," *Carnegie Institution of Washington, Publ. No. 31.*

[2] N. L. Bowen, "The Melting Phenomena of the Plagioclase Feldspars," *Am. Jour. Sci.* (4), XXXV (1913), 583.

[3] *Ibid.*, p. 597.

respect from the pyroxenes described. Nevertheless the exact determinations of solidus and liquidus affords a sound foundation for the discussion of zoning in the plagioclases.

When the cooling is at such a rate that zoning results, the composition of the liquid is continually offset toward pure albite. There is a certain definite rate of cooling which gives maximal zoning, in which case the last minute quantity of liquid as well as the outer zone of the crystal has the composition of pure albite, whatever the total composition of the original material may have been. With a somewhat quicker rate of cooling, the range of zoning is not so great owing to a moderate degree of undercooling, and when the undercooling is very great there is no zoning at all. With a rate of cooling somewhat slower than that which gives maximal zoning, the range of zoning is, again, not so great, owing to the opportunity afforded for partial adjustment of composition between the various zones, and when the cooling is extremely slow there is no zoning at all on account of perfect adjustment. Since zoning is absent in this latter case of extremely slow cooling, there is no continuous offsetting in the composition of the liquid in the direction of pure albite from that cause, but the great opportunity for the settling of crystals afforded by slow cooling enters into the problem with the tendency to produce the same result. It is therefore clear that the tendency toward the continuous offsetting in the composition of the liquid increases with slow cooling.

CRYSTALLIZATION IN THE SYSTEM DIOPSIDE-ANORTHITE-ALBITE

It was with the purpose of showing the manner in which the properties of plagioclase mixtures are carried into polycomponent systems that the investigation of the ternary system diopside-plagioclase was undertaken, and fortunately definite results were obtained.

Fig. 6 is the equilibrium diagram. All liquids whose composition is represented by points in the field *BCED* are capable of existing in equilibrium with plagioclase, and all liquids in the field *AED* may exist in equilibrium with diopside; consequently all liquids represented by points lying along the boundary curve *DE* can exist in equilibrium with both plagioclase and diopside. In

Fig. 7 the temperature relations of the fusion surface are indicated by means of isotherms or temperature contours. The isotherms indicate the shape of the fusion surface in the same manner that elevation contours represent the shape of the surface of the ground on a topographic map, the contour interval being a certain number of degrees instead of a certain number of feet. Any point on Fig. 7

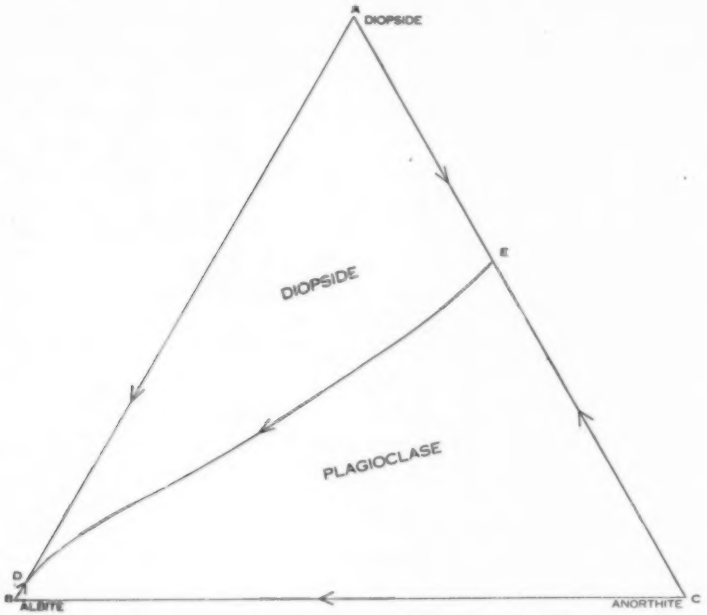

FIG. 6.—Field diagram of the system: diopside, plagioclase

represents, therefore, not only a definite composition, but also a definite temperature. Any point within the plagioclase field represents the composition of a liquid which can exist in equilibrium with plagioclase and at the same time represents the temperature at which that liquid becomes just saturated with plagioclase.

The crystallization of typical mixtures may now be considered. On account of the occurrence of a mix-crystal series it is necessary to distinguish, as was done in the system involving the pyroxene

series, between the two types of crystallization, that in which perfect equilibrium is obtained and that in which zoning occurs.[1]

Crystallization with perfect equilibrium.—A liquid of composition *F* (Fig. 8) which contains 50 per cent labradorite (Ab_1An_1) and 50 per cent diopside begins to crystallize at 1275°, diopside separating first. As the temperature falls the composition of the liquid

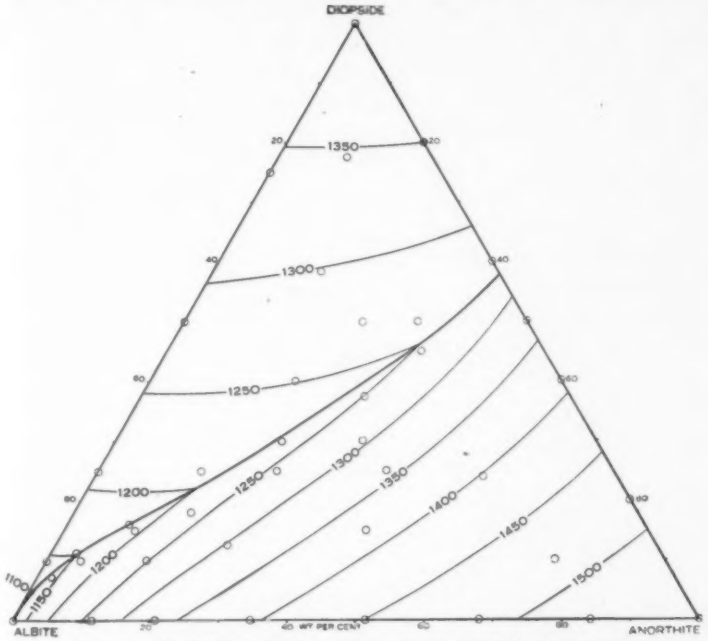

FIG. 7.—Equilibrium diagram of the system: diopside, plagioclase

changes from *F* along *AFG* (directly away from diopside), and when the temperature 1235° is reached the mass consists of 17 per cent diopside crystals and 83 per cent liquid of composition *G*. At this temperature bytownite of composition *H* (approximately Ab_1An_4) begins to crystallize and the composition of the liquid changes along the boundary curve *DE* toward *D*. Both diopside

[1] These correspond with "Erstarrung zweiter Art" and "Erstarrung erster Art" respectively of Schreinemakers (*Zs. phys. Chemie*, L [1905], 189–90).

and plagioclase continue to separate and the plagioclase crystals, not only those separating at any instant, but also those which had formerly separated, continually change in composition—become richer in albite. At 1220° the whole mass is made up of 37 per cent diopside crystals, 25 per cent labradorite crystals of composition *L* (Ab_1An_2), and 38 per cent liquid of composition *K*. As the temperature falls still lower the liquid gradually decreases in amount

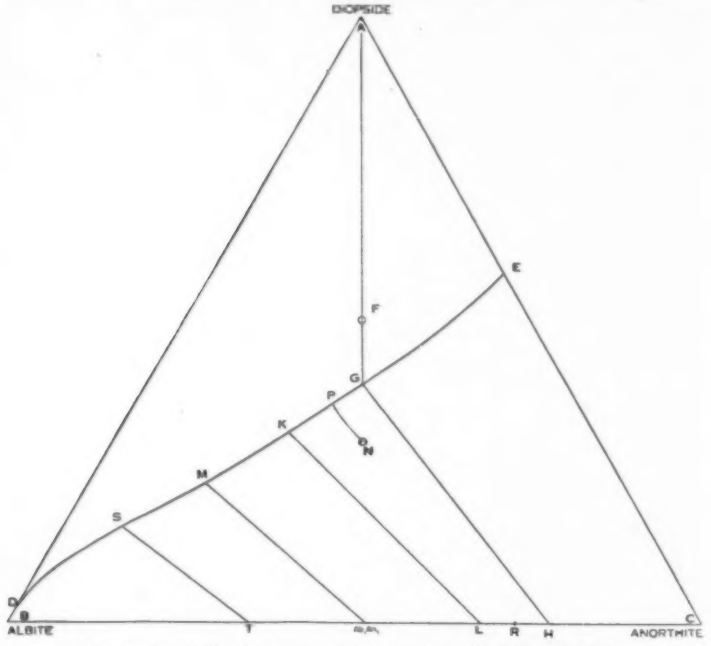

FIG. 8.—Crystallization curves for the system: diopside, plagioclase

and continually changes in composition until at 1200° it is all used up, the last minute quantity having the composition *M*. In the meantime diopside and plagioclase crystals have been separating and the plagioclase has been changing continuously in composition until at 1200°, when the last of the liquid disappears, the composition of the feldspar is Ab_1An_1. The whole mass now consists of 50 per cent diopside and 50 per cent Ab_1An_1.

If the composition of the original liquid is that of the point *N*, which consists of 70 per cent plagioclase Ab_1An_1 and 30 per cent diopside, crystallization begins with the separation of bytownite (Ab_1An_4 approximately) at 1302°. As the temperature falls the composition of the liquid changes, along the curve *NP*, plagioclase continues to separate, and its composition changes until at 1230°, when the liquid has the composition *P*, the feldspar has the composition *R*(Ab_1An_3). With further cooling, the composition of the liquid changes along the boundary curve, diopside separating as well, and, as in the preceding case, the last of the liquid disappears at 1200°, when it has the composition *M*, and the plagioclase crystals have changed gradually to Ab_1An_1. The whole mass now consists of 70 per cent plagioclase Ab_1An_1 and 30 per cent diopside.

The two mixtures *F* and *N* are merely random mixtures of Ab_1An_1 and diopside on opposite sides of the boundary curve. All mixtures of Ab_1An_1 and diopside, therefore, become completely crystallized at 1200°, when perfect equilibrium is obtained, and the last minute quantity of liquid has the composition *M*, which, expressed mineralogically, is 78 per cent Ab_4An_1 and 22 per cent diopside.

All mixtures of diopside with Ab_1An_2 become completely crystallized at 1220°, the last of the liquid having the composition *K*. Mixtures of Ab_2An_1 and diopside are completely crystalline at 1178° and the last of the liquid has the composition *S*. Thus a mixture of diopside with any plagioclase has a temperature of final consolidation different from that of a mixture of diopside with any other plagioclase, and to speak of a eutectic between diopside and plagioclase is to use a meaningless phrase.[1] "The eutectic of plagioclase and pyroxene" is even more emphatically meaningless when the pyroxene referred to is a complex mix-crystal such as augite.

Crystallization with great undercooling.—The same final product will be obtained in each of the foregoing cases if the liquid is greatly

[1] Even the definite temperature of final consolidation of mixtures containing a certain definite plagioclase is not properly to be called a eutectic. Thus 1200° is not the eutectic temperature of Ab_1An_1 and diopside, and the liquid *M* is obviously not the eutectic mixture of Ab_1An_1 and diopside.

undercooled. Thus if the liquid *F* is cooled very quickly to a temperature below 1200°, crystallization, if it takes place at all, will give 50 per cent diopside and 50 per cent plagioclase of the uniform composition Ab_1An_1 (unzoned).

Crystallization with zoning.—When the cooling is too rapid to give crystallization of the perfect equilibrium type and yet not rapid enough to give the great degree of undercooling referred to in the foregoing, the formation of zoned crystals of plagioclase will result. According as the one or the other of the above-named rates of cooling is approached the degree of zoning is reduced to a minimum. With a certain intermediate rate of cooling maximal zoning results. In this case a crystal once separated suffers thereafter no change of composition, the liquid disregarding crystals which have already formed, so that the crystallization of the liquid may be regarded as beginning anew at each instant.

The effect of this action may be realized by considering that during the crystallization of the liquid *F*, as already outlined, the liquid portion is separated from the crystalline portion at a temperature of, say, 1220°. At this temperature the liquid has the composition *K* and we shall imagine that this separated liquid is crystallized under perfect equilibrium conditions. Instead of becoming completely crystalline at 1200°, as it would if the crystals had not been removed, it now becomes completely crystalline only at 1178°, and the final liquid, instead of the composition *M*, has the composition *S*, i.e., is much richer in albite. If the virtual separation of liquid from crystals is a continuous process accomplished through the intervention of zoning, it is plain that the offsetting in the composition of the final liquid is limited only by the eutectic albite-diopside which it actually attains in the case of maximal zoning. This fact is true, not only of the special liquids to which reference has been made, but of *any mixture of anorthite, albite, and diopside whatsoever.*

Crystallization with subsidence of crystals.—The sinking of crystals of plagioclase in a mass of liquid which is very slowly cooled will obviously affect the upper layers from which the crystals have settled in the same manner that zoning affects the residual liquid. The upper layer is continually enriched in albite and its tempera-

ture of final consolidation continually lowered. This latter effect is impossible in any eutectic system. Moreover, the temperature of final consolidation of the lower layers is continually raised.

The effect of rate of cooling summarized.—When the liquid is very quickly cooled, it crystallizes quickly, if at all, and with little or no tendency to an offsetting in the composition of the liquid. If it is cooled moderately slowly, zoning of the plagioclase causes a continual enrichment of the residual (interstitial) liquid in albite. If it is cooled still more slowly, sinking of plagioclase causes a similar continual enrichment of the residual (upper) liquid in albite. In favorable cases the final liquid may be *more than 90 per cent albite* even although the original mixture were, say, 50 per cent diopside and 50 per cent bytownite.

CONCLUSIONS TO BE DRAWN FROM THE INVESTIGATED TERNARY SYSTEMS

If we now combine the information furnished by the investigated systems, important conclusions may be drawn with regard to the crystallization of basaltic magma under various conditions. Instead of the simple pyroxene diopside, present in the mixtures of the last system discussed, we may consider one of the intermediate pyroxenes, which melt with decomposition and the formation of olivine, to be present in addition to plagioclase. Rapid cooling of such a liquid would give merely plagioclase and pyroxene. On the other hand, slow cooling permits radical variation from this simple result. The early formation of olivine brings about an excess of free silica in the residual liquid if any process intervenes to prevent the resorption of the olivine by the liquid. The early formation of very calcic plagioclase brings about an enrichment of the liquid in albite if anything intervenes to prevent the continual alteration in the composition of the crystals by interchange with the liquid. Finally the early formation of magnesia-rich pyroxene brings about an enrichment of the liquid in diopsidic pyroxene if similar conditions intervene.

The sinking of crystals affords a means of continually separating crystals from the part of the liquid in which they formed and is therefore a process which will give the results just outlined. If, therefore, the mixture of plagioclase and pyroxene referred to were cooled

slowly and continual sinking of crystals occurred, the inevitable result would be a body consisting of calcic plagioclase, olivine, and magnesian pyroxene in its lower parts (i.e., of a gabbroidal nature) and of sodic plagioclase approaching albite, diopsidic pyroxene, and free silica in its upper parts (i.e., of a granitic nature), with various intermediate types in the intermediate layers. If the freedom of sinking of crystals were somewhat restricted, one of these intermediate types, say a granodiorite or a diorite, would occur as the uppermost differentiate, the limit of the process under these less favorable conditions. The composition of the residual liquid might, moreover, have been similarly affected by zoning of crystals even if there were no opportunity for the sinking of crystals, and in this case the *interstitial* material of late crystallization would be the same salic material as that found in the upper layers when sinking of crystals took place. If a certain amount of both zoning and sinking of crystals took place, a body would result showing the salic differentiate both as interstitial material and as a separate upper layer. The same possibilities of the formation of peridotite and spinel-bearing peridotite obtain in this case with the same conditions favoring their formation as those discussed under the anorthite, forsterite, silica system.

It has been possible, then, to deduce from facts ascertained experimentally the crystallization with quick and slow cooling of mixtures which give results closely analogous to the occurrence observed in nature of diabase in small dykes and small sills (quickly cooled) and of diabase with micropegmatite interstices or a granitic or granodioritic differentiate in larger bodies (slowly cooled). There are many differences and complications in the natural magma in the matter of details, but it is clear that the broad scheme is well understood and that crystallization is the sole control. There is no necessity for assuming that assimilation of siliceous material is essential to the formation of the salic differentiate, nor that its separation is accomplished by the process of liquid immiscibility. The Palisade diabase sill with its "ledge" rich in sunken olivine crystals near the base and the micropegmatite interstices in the main mass of the diabase is a case in which the working of the process is clearly exhibited.[1]

[1] J. V. Lewis, *Ann. Rept. State Geologist, New Jersey*, 1907, p. 125.

THE IMPORTANCE OF THE FORMATION OF BIOTITE

Considerable importance has been attached in the foregoing to the early separation of olivine, but there are many cases of diabases with micropegmatite interstices, or even a separate salic differentiate, where there is good evidence that no early separation of olivine took place. Whence, then, came the free silica (quartz)? It is, of course, possible in some instances that the magma as intruded was a quartz-diabase magma; yet in many cases the quickly cooled, small dykes show no quartz, and prove clearly that the magma was of normal, basaltic type. There must be some process which results in the separation of free silica as quartz entirely independent of the separation of olivine in some cases, supplementing it in others. This process is that involved in the separation of the mica, biotite. The femic material which separates as pyroxene from the more basic diabase, and dominantly as hornblende in rocks of intermediate composition, appears in solid solution with alkalic molecules as biotite-mica in the salic differentiates. It is frequently noted, moreover, that when the salic material occurs rather as interstitial micropegmatite, the micropegmatite liquid where it bordered against pyroxene has reacted with it to form biotite. This difference between the natural magma and the artificial melts in which a diopsidic granite was the salic differentiate is plainly the outcome of the fact that the artificial melts are anhydrous whereas the magma contains various volatile constituents. The formation of hornblende and still more of the micas, with their essential content of water and often of fluorine, is the result of an increasing concentration of volatile constituents.

The change in the nature of the ferromagnesian constituent with the progress of crystallization has not been investigated experimentally on account of the great difficulty of dealing with iron-bearing minerals. The principles involved are, however, well illustrated in certain investigated systems and will be pointed out before proceeding to a discussion of the processes taking place.

EQUILIBRIUM IN SILICATE LIQUIDS

It is sometimes possible to obtain, from a study of the crystallization of certain mixtures, definite evidence of equilibrium reactions in the liquid.

If a liquid of composition $MgSiO_3$ is cooled, the first compound which separates is Mg_2SiO_4 (forsterite). There is, therefore, direct evidence that the compound $MgSiO_3$ is partly dissociated in the liquid state in such a manner that Mg_2SiO_4 is one of the dissociation products. A possible equation for the equilibrium reaction might be written $2MgSiO_3 \rightleftharpoons MgSiO_4 + SiO_2$. There may be, indeed probably there is, further dissociation according to the reaction $Mg_2SiO_4 \rightleftharpoons 2MgO + SiO_2$, but of this there is no direct evidence. There is certain evidence of the presence of Mg_2SiO_4 because that compound first crystallizes from the liquid; i.e., of all the possible compounds which might exist in the liquid, Mg_2SiO_4 first exceeds its solubility. The actual amount of the compound Mg_2SiO_4 may be quite small compared with the amount of undissociated $MgSiO_3$, but the solubility of the latter very much greater. Indeed, it may be stated that, on account of the higher melting-point of Mg_2SiO_4, it may be expected to exceed its solubility before $MgSiO_3$, even if present in the liquid in smaller amount.

If a mixture of Mg_2SiO_4 and anorthite, containing approximately twice as much anorthite as forsterite, is melted and then cooled, the mineral which crystallizes first is neither anorthite nor forsterite, but spinel, $MgAl_2O_4$.[1] There is, therefore, evidence of an equilibrium reaction in the liquid of which one of the products is $MgAl_2O_4$. It is uncertain what other products may be present, but of all those present the compound $MgAl_2O_4$ exceeds its saturation limit first. Magnesia was added to the mixture in the form Mg_2SiO_4 and separates from it as $MgAl_2O_4$, but this should not be construed as meaning that magnesia has a *greater affinity* for alumina than for silica. The actual amount of unchanged Mg_2SiO_4 in the liquid may have been many times as great as the amount of $MgAl_2O_4$,[2] but the solubility of Mg_2SiO_4 correspondingly greater. Solubility is the controlling factor. The solid phases (crystals) which separate from any liquid mixture of silicates cannot be regarded, therefore, as giving unqualified evidence of the relative

[1] Olaf Andersen, *op. cit.*, p. 436.

[2] The separation of $MgAl_2O_4$ even when these molecules occur in the liquid in relatively small amount is connected with its high melting-point.

affinity of the various oxides for one another.[1] Some molecules not represented in the crystalline product, because relatively very soluble, may have been present in the liquid in much greater concentration than those molecules which happened to separate as crystals. Only a complete knowledge of the relative proportions of all the compounds existing *in the liquid* could decide the question of relative affinities. Thus it is sometimes stated that potash has a greater affinity for silica than soda because certain rocks contain orthoclase ($KAlSi_3O_8$) and nephelite (principally $NaAlSiO_4$), but all that can be safely deduced from the association of these two minerals is that among all the compounds in the liquid magma these two were relatively insoluble under the conditions there prevailing. There may have been much more combination in the liquid into the molecules $NaAlSi_3O_8$ and $KAlSiO_4$. That there was at least some combination of this kind is plainly brought out by the fact that the orthoclase is never free from albite, nor the nephelite from kaliophilite.

For a similar reason statements concerning the relative strength of acids, e.g., silicic and carbonic acids, should be guarded. At first sight the reaction $BaCl_2+H_2SO_4=BaSO_4+2HCl$ might be considered to indicate that sulphuric acid is a stronger acid than hydrochloric acid, but we may immediately write the reaction $Ag_2SO_4+2HCl=2AgCl+H_2SO_4$, which, on the same basis, would prove the opposite. As a matter of fact, it is the extremely limited *solubility* of barium sulphate and silver chloride which determines the fact that both these reactions proceed practically to completion. If silicic and carbonic acids occur together in a solution, all we know is that both will exist in a very great variety of combinations; those with which we shall become acquainted in the crystalline state will be those which happen to exceed their saturation limit under the particular conditions.

It is clear then that in the discussion of the crystallization of a magma references to relative affinities should, in general, be avoided for the reason that the crystalline (least soluble) phases give no evidence on that subject. The crystalline product may,

[1] See Johnston and Niggli, "The General Principles Underlying Metamorphic Processes," *Jour. Geol.*, XXI (1913), 506–8, 513.

however, give evidence of the existence of certain equilibrium reactions in the liquid, though leaving in doubt the relative proportions of the various compounds taking part in the equilibrium.

EQUILIBRIA IN MAGMAS INDICATED BY MINERALS PRECIPITATED

We may now return to the commonly observed association of diabase and its salic differentiate. The principal minerals of the salic differentiate are orthoclase, sodic plagioclase, quartz, and biotite. It appears that special attention has seldom been called to the fact that in the *most siliceous rocks* (granites, granodiorites, etc.) considerable proportions of the alkalis and of the ferromagnesian constituents are represented, in the mineral biotite, in their *least siliceous* combinations.[1] A consideration of the equilibria in the magma indicated by this mineral grouping affords an explanation of the formation of such a differentiate when diabase magma is slowly cooled, and at the same time leads naturally to a conception of one of the modes of origin of the most important group of the alkaline rocks, the nephelite syenites and their derivatives.

Imagine a large body of basaltic magma slowly cooled and crystallizing in such a manner that the early-formed pyroxenes and more calcic plagioclases sink slowly in the liquid. The result is a continual enrichment of the part still liquid in alkaline feldspars. There is also a continual enrichment in the volatile constituents such as water, CO_2, S, Cl, etc. From this liquid are precipitated the minerals of the salic differentiate including alkaline feldspars, quartz, and biotite. The chemical characters of these minerals give direct evidence of a number of equilibrium reactions in the liquid. The most important of these reactions involve the breakdown of part of the polysilicate molecules as follows:

$$KAlSi_3O_8 \rightleftharpoons KAlSiO_4 + 2\ SiO_2$$
$$NaAlSi_3O_8 \rightleftharpoons NaAlSiO_4 + 2\ SiO_2$$

There must also exist such equilibria as the following:

$$NaAlSiO_4 + H_2O \rightleftharpoons HAlSiO_4 + NaOH$$
$$KAlSiO_4 + H_2O \rightleftharpoons HAlSiO_4 + KOH$$

[1] See Iddings, *Igneous Rocks*, I, 133.

and, doubtless,

$$NaOH + HCl \rightleftharpoons NaCl + H_2O$$
$$2\,NaOH + H_2S \rightleftharpoons Na_2S + 2\,H_2O$$
$$2\,NaOH + CO_2 \rightleftharpoons Na_2CO_3 + H_2O$$

with similar reactions for the corresponding potash compounds, besides very complicated equilibria between the molecules S, SO_2, SO_3, C, CO, CO_2, H_2S, H, H_2O, O, HCl, Cl, etc.

Though we understand very little about the exact form in which iron and magnesia enter into the micas, it appears that there is the same tendency to partial breakdown from the more siliceous metasilicate to the less siliceous orthosilicate.

There is no doubt that the increased concentration of water in the magma at this stage exerts a strong influence in promoting this breakdown of the polysilicate molecules of the alkalis and the metasilicates of iron and magnesia into the orthosilicate molecules with setting free of silica, an action which may be compared with hydrolysis. Niggli[1] ascribes such action to water in discussing the rocks of Electric Peak and Sepulchre Mountains described by Iddings.[2] In some of the deep-seated rocks of Electric Peak quartz and biotite occur, whereas they are absent in surface rocks of the same composition at Sepulchre Mountains. This is ascribed to loss of water by the surface rocks. Niggli states: "Zugleich hat dieses Wasser offenbar einen Teil der Kieselsäure aus den Verbindungen gedrängt und so in der Tiefenfazies zu freiem SiO_2 geführt." It is also well known that a hornblendic rock without quartz may, even after complete solidification, be changed to a biotite-quartz rock during metamorphism, when there is special activity of volatile constituents, including water. An example has been described by Cushing.[3]

It is not to be imagined that any of these reactions in the magma begin abruptly at any special stage in the history of the magma. For any given concentration of the molecules $KAlSi_3O_8$

[1] "Die gasförmigen Mineralizatoren im Magma," *Geologische Rundschau*, Band III (1912), 479.

[2] *U.S. Geol. Survey, 12th Ann. Rept.*, I, (1891), 657; Iddings, *Igneous Rocks*, I, 152–53.

[3] "Geology of the Thousand Islands Region," *N.Y. State Museum, Bull. 145*, p. 40.

and $NaAlSi_3O_8$, however small, there is a certain corresponding concentration of $KAlSiO_4$, $NaAlSiO_4$, and SiO_2. During the *slow* crystallization of the basaltic magma, with the continual increase in the concentration of $KAlSi_3O_8$, $NaAlSi_3O_8$, and the promoting agent water, there is a corresponding increase in the concentrations of $KAlSiO_4$, $NaAlSiO_4$, SiO_2, and others, until finally some of these exceed their saturation limit. SiO_2 then separates as quartz; $KAlSiO_4$ with $HAlSiO_4$, certain complex ferromagnesian molecules, and a limited amount of $NaAlSiO_4$ separate as a solid solution making up the mineral biotite. The molecules which separate are not necessarily the most concentrated; certain others may be much more concentrated, but correspondingly more soluble. Neither is it necessary that the molecules separate in the stoichiometric proportions represented by the reactions given. They are formed in the liquid in these proportions, but the extent of their separation from the liquid is determined by their solubility relations. The relative amounts of quartz and biotite contained in a given rock have, therefore, no necessary relation to the proportions of the various molecules indicated in the foregoing reactions. Indeed, quartz, the one product of these reactions, usually is greatly in excess of biotite, a grouping of several of the other products. This means that there is a relative storing up in the liquid of the molecules, other than SiO_2, which result from these reactions. The molecules stored up are, then, principally the aluminous orthosilicates of the alkalis, a fact of great significance in its bearing on the origin of nephelite syenites.

THE CRYSTALLIZATION OF BASALTIC MAGMA

Let us now review briefly the crystallization of a magma of basaltic composition. If the magma is cooled very rapidly, it crystallizes rapidly, giving simply a diabase. If there is rather slower cooling, there may be a limited amount of sinking of crystals of the early-formed pyroxene and more calcic plagioclase, and a consequent enrichment of the uppermost liquid in alkaline feldspar, giving a diorite as a light, upper differentiate. If the cooling is still slower, there is more prolonged opportunity for the sinking of crystals and the liquid may be sufficiently enriched in alkaline feldspar

molecules and water to give a high concentration and consequent separation of some of those molecules which are formed by the breakdown of the alkaline feldspar molecules (biotite or quartz or both). Thus may originate a quartz-diorite as a salic differentiate, or with still slower cooling a granodiorite or a granite. When cooled somewhat too quickly to allow appreciable settling of crystals, zoning of plagioclase crystals may bring about the same effect on the liquid, and the salic types mentioned above may occur as interstitial material.

From some basaltic magma the early formation of olivine may take place, with the result that the amount of possible salic differentiate is augmented. This early separation of olivine may occur during the slow cooling of a magma which with quick cooling gives no olivine but only plagioclase and pyroxene. Further, from some basaltic magma, which even with quick cooling gives considerable olivine, spinel may be formed among the products of early crystallization when the cooling is slow (see p. 30). Peridotite or spinel-bearing peridotite may, therefore, be formed by collection of the early crystals and the salic differentiate be thereby increased.

The crystallization of a normal basaltic magma always tends toward biotite granite, but the biotite granite stage is reached only with slow cooling. With somewhat quicker cooling, the process of sinking of crystals cannot keep pace with the quicker using up of the liquid, owing to more rapid crystallization. Crystallization and therefore differentiation becomes complete at the granodiorite, quartz diorite, or diorite stage according to the rate of cooling. It is clear that a dioritic border phase occurring about a granite or granodiorite mass is to be attributed to the fact that cooling at the border was maintained considerably in advance of that farther away from the border, and not to any diffusion of basic material toward the cold wall. In the cooler outer portion, crystallization was complete at the diorite stage, but in the warmer interior, differentiation by removal of crystals continued till the later stage of granodiorite or granite.[1] Daly's explanation of basic

[1] B. S. Butler has come to this conclusion in the case of a great number of stocks in different sections of Utah (personal communication from Mr. Butler shortly to be published in *Economic Geology*).

border phases is therefore substantially correct. It is not, however, necessary that the border phase is the undifferentiated original magma. It is better stated in the more general form that the border phase represents a less advanced stage in the differentiation of the magma. A satellitic stock of, say, diorite occurring in connection with a granitic batholith is to be explained similarly.

The occurrence of a basic marginal phase at the top of a batholith is a reversal of the general arrangement according to density which results from the free working of the processes of differentiation. This is not due to the action of any positive process tending to produce movement of material of early separation in the opposite direction, but to the constant tendency of cooling to put an end to the gravitative process. It is to be noted that the basic border phase is a completely frozen, solid rock during the period of continuance of differentiation in the liquid immediately below it. There is no violation of the law of gravitation. If a piece of the solid rock becomes broken off, it will, of course, sink in the liquid, but only then. It is in this manner that many basic cognate xenoliths are formed. It is clear also that the salic phase may be injected into fractures in the frozen border types formed from the same magma. The observance of this phenomenon is not to be considered as indicating any considerable difference in age.

FIELD EVIDENCES OF THE CONTROL OF CRYSTALLIZATION IN DIFFERENTIATION

The foregoing deductions relative to the course of crystallization and therefore of differentiation are fully supported by field evidence. Daly's experience has led him to the same conclusion with regard to the results, though the attainment of the results is differently explained by him. Speaking of his theory he states: "It considers the final acid pole of splitting in large post-Keewatin batholiths as granite." When differentiation is "arrested midway" "rocks of intermediate composition result."[1] He rightly considers that an intermediate rock such as diorite is the result of arrested differentiation and not an anchi-eutectic rock formed by the crystallization of a *final* eutectic liquid beyond which differ-

[1] *Igneous Rocks and Their Origin*, p. 361.

entiation cannot proceed. The use of the word "splitting" indicates that Daly considers that the medium of accomplishment of differentiation is liquid immiscibility, a process of which there is no clear evidence and of which a detailed description applied to rocks has never been offered by any investigator. The facts are, however, in perfect accord with the details of differentiation by crystallization given in the present paper.

The gravitative arrangement of the various differentiates of the Moyie sills and their individual mineralogy are absolutely that to be expected if differentiation by crystallization as outlined is the sole control.[1] They vary from normal diabase through hornblende diorite to biotite granite.

Somewhat similar sills in the Gowganda Lake District of Ontario, described by the writer, have essentially the same relations. In the original paper it was considered that the surrounding sediments played an important part in the formation of the granophyric bodies at the upper surface of the sills.[2] This opinion was arrived at principally because of the difficulty of picturing any process of pure differentiation whereby a quartzose rock could be formed from basaltic magma. With this difficulty removed the writer has no hesitation in concluding that the granophyre and the micropegmatite interstices of the diabase were formed after the manner detailed in the present paper and that interchange of material between the granophyre and adinolized sediment was a subsidiary process[3] contributing to the soda-rich nature of the border phases.

The great sheetlike mass at Sudbury with granite in the upper part and norite in the lower shows the same type of crystallization differentiation controlled by gravity.

There are also many cases of this general type with the additional feature that peridotite occurs as a basal differentiate. The Duluth laccolith, closely related in age and in origin to the Sudbury mass, is a case in point.[4]

[1] Daly, *Am. Jour. Sci.* (4), XX (1905), 187; Schofield, "The Origin of Granite (Micropegmatite) in the Purcell Sills," *Geol. Survey Canada, Museum Bull. No. 2*, pp. 1–34.

[2] N. L. Bowen, *Jour. Geol.*, XVIII (1910), 658.

[3] Cf. Collins, *Geol. Survey Canada, Mem. 33*, pp. 59 f.

[4] W. S. Bayley, *Jour. Geol.*, II (1894), 814.

It has been pointed out in the discussion of crystallization that the olivine-rich portion (peridotite) would be completely crystalline while the remaining portion was still liquid and that the same is true of the gabbro portion with respect to the siliceous differentiate. If gravitative differentiation took place under perfectly quiet conditions, the relations between the types would be transitional, but any disturbance of the mass during consolidation might cause the gabbro to have an intrusive relation to the peridotite, owing to the injection of dykes into cracks, and the granite to have a similar relation to the gabbro. In the Duluth laccolith the granitic phase has this intrusive relation.

Harker describes the intrusive igneous complex of the Cuillin and Red Hills as consisting principally of three laccoliths of peridotite, gabbro, and granite respectively.[1] In view of what has been ascertained concerning the course of crystallization in artificial melts which have a direct bearing on the question of crystallization of basaltic magma, the writer is emboldened to offer the following alternative suggestion. The igneous mass referred to may be, for the most part, one laccolith with a general eastward dip, formed as the result of a single *principal* act of intrusion of magma of the same composition as that extruded in colossal quantity during the fissure-eruptions. Rapid cooling of this magma in the flows gave basalts rather unusually *rich in olivine*. Slow cooling of the same magma in the laccolith, accompanied by sinking of crystals, would give, as we may deduce from experimentally ascertained facts, *spinel-bearing peridotite*[2] toward the western margin or base, gabbro at intermediate levels, and granite toward the eastern margin or top, the granite itself becoming more acid eastward, as Harker has observed. The intrusive relation of the gabbro against peridotite and of granite against gabbro would then be referred to movements during consolidation, of which there is abundant evidence.

[1] "The Tertiary Igneous Rocks of Skye," *Mem. Geol. Survey United Kingdom*, 1904.

[2] It is possible that even the common types of basaltic magma, not especially rich in olivine, will give spinel as an early precipitate if very slowly cooled, for in the reverse process—slow heating of the Palisade diabase of New Jersey—Merwin has witnessed the formation of a spinel-like mineral. Cf. Sosman and Merwin, "Data on the Intrusion Temperature of the Palisade Diabase," *Jour. Wash. Acad. Sci.*, III (1913), 392.

The quite exceptional degree of interaction between any two types when one is injected into the other during these movements is due to the fact, to be expected on the present supposition, that the invaded rock, though solid, was still hot, as Harker has supposed it to be. The marked amount of solution of the peridotite by the gabbro is simply the same reaction that would have happened between the liquid and the individual olivine crystals had they not collected into a body. The remarks made on p. 31 with reference to the eruptibility of peridotite to form separate intrusions of that rock would presumably apply to this natural example.

The igneous complex of the Nischne-Tagilsk region in the Urals is intrusive into Devonian sandstones, limestones, and basic lavas. As mapped by Wyssotsky[1] it appears to be, like the Iss complex, a concordant intrusion and suggests a sheetlike mass, dipping eastward, with the important platinum-bearing peridotite and pyroxenite near its base and, passing eastward (upward), successively gabbros, diorites, quartz diorites, and finally granites extending beyond the region mapped. From the present point of view the pyroxenite bodies occurring as borders about the dunites (collected olivine crystals) are *huge reaction-rims* formed in the same general manner as the borders of pyroxene seen about individual olivine crystals in a great variety of rocks (see Fig. 9).

To the writer it seems that some of these examples, especially the Skye complex, form an excellent transition type from those in which movements have been practically absent and the relation between the various rock-types is transitional, through those in which the transitional relations are destroyed and even the simple gravitative arrangement is on the verge of destruction as in the Skye example, to those in which the evidence for both of these has been obscured and for which the gravitative control of differentiation is, therefore, not demonstrable. The Cortlandt series of New York state which presents types more or less parallel to those described by Harker though richer in varieties may, perhaps, represent the last condition.[2]

[1] *Mém. Comité Géol. de la Russie*, Nouv. sér., livr. 62, 1913.

[2] G. H. Williams, *Am. Jour. Sci.* (3), XXXIII (1887), 33; G. S. Rogers, *Ann. N.Y. Acad. Sci.*, XXI (1911), 11–86.

Igneous complexes consisting of dykes, sheets, flows, and bodies without visible floor quite often show the same general association of types as that pointed out in the foregoing, and even with

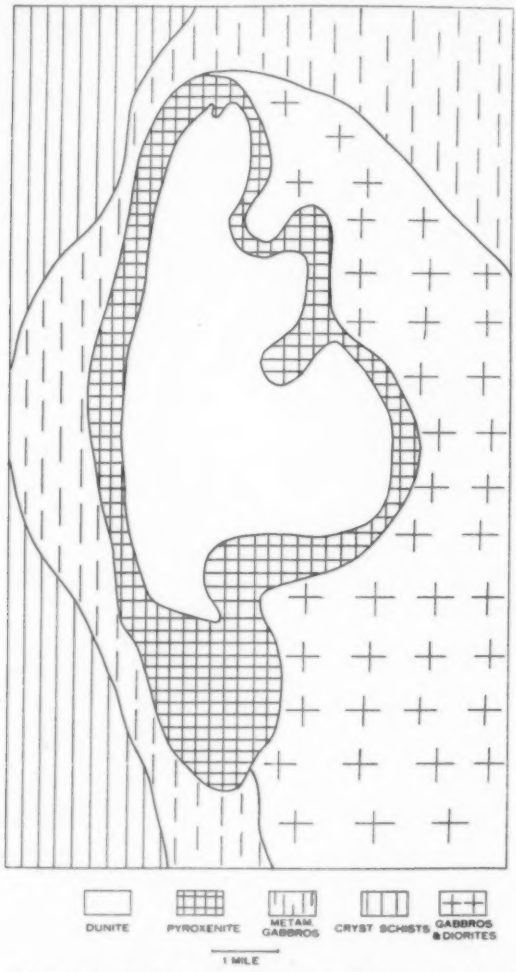

FIG. 9.—Map of the Tagilsk platinum center, Ural Mountains, after Wyssotsky, *op. cit.*, and Duparc, *Arch. Sci. Phys. et Nat., Genève*, XXXI (1911), 216.

these the control of gravity may be reasonably inferred, though the heavier differentiates may occur at unobservable depth in the case of the larger intrusions. In the following a few such bodies are described and in some cases the facts on which the foregoing inference may be based are stated.

The Hope batholith, a late portion of the Coast Range batholithic complex sectioned by the Fraser River Valley, illustrates differentiation on a huge scale, as does its southward continuation the Chilliwack batholith.[1] The types represented vary continuously from gabbro-diorite to granite, and the mineralogy of the individual types is instructive in this connection. The gabbro-diorite is a labrodorite-hypersthene rock. As the plagioclase becomes more sodic, hornblende replaces hypersthene, at first partially and finally completely. Biotite then begins to take the place of hornblende, but only in those phases which have also free quartz, and as these two appear, orthoclase also becomes important. Finally when quartz and orthoclase are fairly abundant, biotite becomes the dominant colored constituent.[2]

Precisely the same type of differentiation is shown in the plutonic complex in the vicinity of Hedley, the variation being from gabbro to biotite granodiorite. The relations at this place are such as to indicate that assimilation had no part in the formation of the salic types. The small and quickly cooled satellitic stocks and sills of gabbro and the diorite-gabbro phase occurring as a chilled border, representing restricted differentiation, about the somewhat larger quartz diorite stocks seem to show that the original magma when it arrived at its present level was still normal gabbroic magma and had not been acidified. Crystallization and the settling of crystals from this magma gave rise to the diorite in the stocks and, in a more advanced form, to the granodiorite of the batholithic mass.

The dioritic intrusives of the Prince of Wales Islands, Alaska, satellitic to the Coast Range batholith, show this same tendency

[1] R. A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Survey Canada, Mem. 38*, p. 534.

[2] N. L. Bowen, *Guide Book No. 8*, Part II, XII^me^ Congrès Géologique International, 1913, p. 258, mentioned there under the field designation "hornblende-rich granitic rocks" on account of the dominance of the intermediate types.

toward a more basic nature of small bodies as compared with the more acid nature (granodiorite and granite) of the larger bodies of the main range.

The same may be said of the gabbro-quartz monzonite series of the Boulder batholith and its satellitic stocks in Montana. Again, in the Sierra Nevada, as represented in the Pyramid Peak area described by Lindgren,[1] a series of the same type is shown.

The relations of the various types of the great igneous complexes of the Coast Range and of the Sierra Nevada seem to the writer strongly to favor the opinion that all of the magma concerned in the formation of the deep-seated bodies arrived practically in the position in which we find these bodies, as *basaltic magma*. Where the magma occurred as a small body it crystallized quickly to a diabase or gabbro. This gabbroic phase may, moreover, occur as a marginal phase about a larger body whose main visible portion is diorite, the diorite being formed, *practically in place*, by the sinking out of crystals from basaltic magma. In still larger bodies a more prolonged period of sinking out of crystals has left the main visible portion a quartz diorite or a granodiorite, again formed in place, with perhaps a border phase of diorite where the process has been somewhat restricted. The magma may, of course, be injected into the surrounding rocks at any late stage and form there small dykes, etc., of the more acid types, but this fact should not be allowed to obscure the plain tendency of the acid rocks to occur principally as large masses and of the basic rocks to occur exclusively as relatively small masses.

Since the granodiorite magma comes into being only by virtue of the very slow cooling of the larger bodies, it is still liquid long after the diorite is a solid rock, and the same is true of diorite magma with respect to gabbro. Such disturbances as may occur during the consolidation of the complex may therefore cause the granodiorite to acquire an intrusive relation against the diorite and the diorite against gabbro. These relations are not to be considered as indicating the order of arrival of magmas from the depths, the order being due to a supposed primary or deep-seated differentiation. The observed sequence is to be explained rather on the basis of a

[1] *Am. Jour. Sci.* (4), III (1897), 301.

single, principal act of intrusion of basaltic magma with subsequent differentiation practically in place and controlled in a general way by the size and rate of cooling of the individual bodies formed. The sequence of intrusion observed is the result of a sequence of consolidation[1] and of movements, resulting in a certain amount of injection of one type into another, which may be wholly of a minor nature and quite subordinate as compared with the main act of intrusion of basaltic magma. In some localities more than one principal intrusion of basaltic magma took place, and therefore two or more interlocking gabbro-granite sequences may exist, with resultant irregularities in the order of succession.

The wholly random spatial arrangement of granite, granodiorite, monzonite, etc., often observed in the larger bodies plainly cannot be the result of differentiation alone, whatever kind of differentiation one may have a leaning toward. The arrangement is the result of movements following differentiation and should not, by itself, be made the basis of either affirmation or denial of gravitative differentiation. Nevertheless, the differentiation is of the type which in other cases is clearly due to a separation of liquid from crystals (fractionation),[2] either by the sinking of crystals or by the squeezing out of residual liquid, a fact which is sufficient to establish a strong presumption in favor of these processes even when they are not demonstrable.

THE ALKALINE ROCKS

NEPHELITE SYENITES AND RELATED TYPES

Biotite granite is, however, not necessarily the end or pole in the process of differentiation which has been outlined. The process may end and, very often, does end at this stage just as it sometimes ends at the granodiorite or diorite stage if the cooling is at the proper rate. Indeed, if magmas were anhydrous, we may conclude from the information furnished by the investigated systems that a granite would be the necessary end beyond which differentiation could not proceed; not a biotite granite, however,

[1] See Ussing, *Geology of the Country around Julianehaab, Greenland*, p. 312.

[2] See A. Knopf, *U.S. Geol. Survey, Bull. 527*, p. 35, on the origin of aplites associated with quartz monzonite of the Boulder batholith.

but rather one characterized by diopsidic pyroxene. But such granites are rare—many times less common than hornblende granites, and these in turn many times less common than biotite granites. The formation of the molecules which enter into the make-up of biotite results from various equilibrium reactions in which water plays an essential rôle. If any of the products of these reactions are removed from participation, through continuance of the processes of separation of liquid from crystals, further differentiation beyond the biotite granite stage is thereby permitted.

It has been shown that at the biotite granite stage, and to a lesser extent in preceding stages, reactions take place in the liquid whose principal feature is the breakdown of polysilicate molecules, probably under the influence of water, to the simpler orthosilicate molecules, among them $KAlSiO_4$ and $NaAlSiO_4$. The precipitation of $KAlSi_3O_8$, $NaAlSi_3O_8$, $KAlSiO_4$ in mica, and SiO_2 as quartz means the concentration in the liquid of all the other molecules indicated in the reactions given on pp. 44 and 45. These are principally $NaAlSiO_4$ and the volatile constituents, water, chlorine, etc., with their compounds. If the crystals of the biotite granite stage, including quartz, sink out of this liquid,[1] then the concentration of $NaAlSiO_4$ will finally reach a stage where nephelite will begin to precipitate. There may also result a concentration of CO_2, S, SO_3, Cl, etc., sufficient to cause their precipitation in compounds such as cancrinite, lazurite, hauynite, and sodalite, minerals which are peculiar to nephelite syenites and related rocks.

The field association of many nephelite syenites and their mineralogy point clearly to their crystallization at this stage of the magma. Both the mineralogy of the rocks, and the high fluidity of the magma indicated by quick changes of composition in alkaline rocks point to the high concentration of volatile constituents at this stage.

Differentiation during crystallization from these very fluid magmas will take place very freely and the formation of both

[1] Or, as seems more likely, if squeezing out of residual liquid is accomplished at the appropriate stage. The appropriate time may, perhaps, be that immediately preceding the period of marked resorption of quartz which is well attested in most rhyolites. A very important effect on the future course of the liquid would ensue, analogous to that which results if crystals and liquid are separated when olivine is about to be resorbed.

highly femic and highly alkalic types (rich in feldspathoids) may result. The more "basic" types of alkaline rock are not, however, in all cases basic differentiates from nephelite syenite magma. The reactions preliminary to the separation of quartz and biotite begin at an early stage in the crystallization of basaltic magma, and the separation of these minerals may take place at an early stage, giving rise to quartz diorites or granodiorites. The possibility of the formation of alkalic magma at a stage much earlier than the biotite granite stage is thereby introduced if conditions are favorable. Favorable conditions seem to consist in the opportunity for sinking, not only of the plagioclase crystals and femic minerals, but also of quartz crystals in sufficient amount. Thus may result relatively "basic" alkaline magmas from which such rocks as basanite might be formed, and nephelite syenite itself as a light differentiate.

In passing from the normal biotite granites direct to the nephelite syenites and related rocks, an important stage has been passed over, viz., the stage of the alkaline granites and syenites. Many occurrences, to be referred to later, show that alkaline granites and syenites are intermediate in their time relations between normal biotite granite and feldspathoid-bearing types. These facts find a likely explanation in terms of the general system here outlined. The precipitation from the granite magma of relatively large amounts of potash molecules as orthoclase and of both potash and magnesia as biotite to form normal granite results in a relative concentration of sodic and iron molecules which are precipitated as relatively large amounts of albite and as the alkaline pyroxenes and hornblendes characteristic of alkaline granites, i.e., of this state of precipitation.

In north-central Wisconsin the sequence described by Weidman —gabbro, diorite, normal granite, soda granite, quartz syenite, nephelite syenite—strictly accords with the outline of differentiation offered.[1]

The sequence in Essex County, Massachusetts, studied in great detail by Clapp, might be described substantially by repeating the type names used above in connection with the Wisconsin

[1] *Wis. Nat. Hist. Survey, Bull. 16*, pp. 349 f.

area.[1] It may be noted, moreover, that a broad study of the granites of eastern Massachusetts and Rhode Island, a region which includes the Essex County area, has led Loughlin and Heckinger to the conclusion that the alkaline granites (riebeckite- and aegirite-bearing), though later than the biotite granites, are merely the last product of the general magma represented dominantly by the normal biotite granites[2] and are not separated from them by any important period of time.

A parallel succession, viz., from basic through quartzose to feldspathoid-bearing types, appears to obtain in the post-Cretaceous minor intrusions of the Black Hills of South Dakota.[3] Continuous passage from normal granite through syenite to nephelite syenite is shown in the Bancroft area of Ontario.[4] In this case, typical alkaline granite is suppressed. According to Loewinson-Lessing, the connection of the miaskite (nephelite-syenite) of the Urals with granite has been shown by Beljankin.[5] Kerr concludes that the nephelite syenites, quartz syenites, and other alkaline syenites of the Port Coldwell area are "merely a peripheral differentiation phase of the fundamental gneiss" (granite).[6]

It should be admitted, however, that much is yet to be accomplished before one can speak with much assurance of the physical chemistry of the problems connected with the interrelations of the alkaline rocks. It will probably be a long time before important aid in attacking the questions can be expected from the experimental side, on account of the difficulty of treating systems containing volatile components. Nevertheless, it is clear that the alkaline rocks belong to a stage of great concentration of these volatile constituents and that many of the reactions in the magma depend upon this concentration. The tendency of the increased abundance of these substances, including water and the various mineral acids, is to

[1] C. H. Clapp, *The Igneous Rocks of Essex County, Massachusetts*, abstract of thesis, Massachusetts Institute of Technology, 1910.

[2] *Am. Jour. Sci.* (4), XXXVIII (1914), 55.

[3] J. P. Iddings, *Igneous Rocks*, II, 407.

[4] Adams and Barlow, *Geol. Survey Canada, Mem. 6*, 1910, p. 260.

[5] F. Loewinson-Lessing, "Origin of the Igneous Rocks," *Geol. Mag.*, N.S., Dec. V, Vol. VIII, p. 255.

[6] *Ontario Bur. Mines, Ann. Rept.*, 1910, p. 230.

displace silica from its combinations. Thus is brought about great concentration of the molecules which go to form biotite at the stage of the normal granite, and biotite, together with quartz, is precipitated. From similar causes results the precipitation of the olivine fayalite in the alkaline granites, the felspathoids, and even free alumina in foyaitic rocks. If the question is attacked from this point of view, that is, if the various minerals precipitated at any stage are recognized as those least soluble (in proportion to their abundance) at that stage, if the various equilibrium reactions indicated by these minerals are sought out, and if the effect on these reactions of the removal of minerals is considered, it seems likely that a good understanding of the alkaline rocks might be arrived at from field studies with a certain amount of guidance afforded by experimental work.

Discussion of the question whether alkalic and sub-alkalic rocks may be derived from the same magma has not been included in the foregoing because it is believed that field facts leave no possible doubt in the matter.[1] Crystallization proceeds, apparently, with the precipitation of the constituents of normal granite, then of those of the alkaline granites, through those of the alkaline syenites, to those of the nephelite syenites, with no sharp lines of demarkation anywhere in the series. It is to be remembered that the series will be maintained only when the continual removal of crystals from that part of the liquid in which they formed is likewise maintained.

The genetic relation and continual passage from sub-alkaline to alkaline types is now recognized as true by most petrologists and is, in fact, well illustrated by the difficulty encountered by every petrologist in setting up a boundary between them. There appears to be, however, a peculiar subconscious persistence of the older idea of a genetic separation even in the minds of many who admit a genetic connection. This tendency is apparent especially in nomenclature. A perfectly normal diabasic or gabbroic rock, for example, is likely to be termed an essexite if it occurs in a region of dominantly alkaline rocks and especially if associated with true

[1] See H. S. Washington, "The Volcanic Cycles in Sardinia," *Comple-rendu*, XII^me^ session, Congrès Géologique International, p. 235.

essexite. Such a tendency in naming rocks is to be guarded against, for it covers up facts—in this case the fact of frequent association of normal gabbroic rocks with alkaline types.

LEUCITE-BEARING ROCKS

Rocks bearing leucite are of rare occurrence and their relations are, perhaps, not well enough understood to make clear the manner of their origin. Leucite is sometimes one of the minerals precipitated from a nephelite syenite magma derived, presumably, in the manner already outlined. The relations of some leucite-bearing rocks suggest, however, that differentiation in the magma from which they were formed proceeded along the lines outlined in the discussion of the formation of biotite and that the magma was then intruded to a high level where water could escape more or less freely. The lowering of the pressure of water-vapor lessens the possibility of the formation of those hydrous molecules which go to form mica, and a part of the potash must then be precipitated in some form other than mica, viz., as leucite.[1] Highwood Peak stock, for example, sends out mica-rich dykes, and these, where they cut loose breccias which would facilitate the escape of water, often pass in a single dyke into a leucite-bearing rock, so-called leucite basalt.[2] Iddings has called attention to the fact that some minettes and some leucite basalts have nearly identical composition. Shonkinite, a type comparatively rich in biotite, has no mineralogical equivalent among the effusive rocks, but is represented by its chemical equivalent, which is a leucite rock, owing presumably to the loss of water on extrusion. It seems possible that the gradual escape of water from the outer border of the Shonkin Sag laccolith has given rise to the 5–15-foot border of leucite-basalt which is nearly identical in composition with the shonkinite immediately adjacent to it.[3] If the partial escape of water takes place from a moderately deep-seated body, even though not especially rich in the molecules which go to form mica, it seems possible that further

[1] Cf. H. S. Washington, "The Formation of Leucite in Igneous Rocks," *Jour. Geol.*, XV (1907), 377–79.

[2] L. V. Pirsson, *U.S. Geol. Survey, Bull. 237*, 1905, p. 22.

[3] Pirrson, *Op. cit.*, p. 47.

differentiation, with leucite as one of the crystalline units in that process might give rise to rocks comparatively rich in leucite. The relative abundance of leucite-bearing types as effusive and hypabyssal rocks as compared with their rarity as truly abyssal rocks lends support to the idea that near-surface conditions favor their formation. Such considerations raise the whole question of the extent to which evaporation, on the one hand, and cooling on the other, have controlled the crystallization of a given rock mass.

Under the foregoing conception of the leucite rocks they should presumably belong at a late stage of the genetic sequence, a stage appropriate to the preliminary formation of biotite. This appears to be true of the lavas of the Aeolian Isles as determined by Bergeat, who refers to the leucite types as an old-age manifestation following after a sequence exhibiting increasing acidity.[1]

ESCAPE OF THERMAL WATERS

The crystallization of the constituents of the nephelite syenites and related rocks is not the end of the process of crystallization from the magma. The precipitation of analcite and other zeolites, apophylite, and thomsonite follows thereafter and the process passes on into the stage considered to belong rather to that of thermal waters than to magmas. In these waters there is an increasing concentration of the very soluble salts of the alkalis such as Na_2S, Na_2CO_3, NaCl, etc. (see equilibrium reactions, pp. 44 and 45), and they probably constitute the alkaline ascending waters of primary ore deposits. These waters may, of course, be expelled from the magma at a much earlier stage, say the granitic or granodioritic, if the cooling is at such a rate that differentiation is completed at that stage.

OTHER CONCEPTIONS OF THE ALKALINE ROCKS

Daly has offered a theory of the alkaline rocks in general, which supposes that they are differentiates from subalkaline magmas that have absorbed limestone. The formation of feldspathoids is considered due to a desilication of the magma consequent upon the

[1] A. Bergeat, *Compte-rendu*, XII^me^ session, Congrès Géologique International, Canada, p. 250; "Die äolischen Inseln," *Abhand. der k. bayer. Akademie der Wiss.*, II, Kl., XX, (Munich, 1899), p. 270.

introduction of lime and its subsequent removal as lime silicates during the course of differentiation. The occurrence of cancrinite and primary calcite is considered evidence of the introduction of CO_2.

The fact that limestone may, as a rule, be found in the same general region as alkaline rocks cannot, in itself, be regarded as having any significance, because limestone is of such extremely widespread occurrence. Even in those cases which seem best to indicate some connection between the limestone and the alkaline rock, the application of the theory presents grave difficulties. In the Haliburton-Bancroft area of Ontario, batholiths, dominantly granitic, show nephelite syenites against bordering limestones. The relation is striking, but since the theory demands the absorption of limestone by the magma, and the subsequent formation of the alkaline rock by differentiation from the homogeneous magma, the manner of differentiation should determine the location of the alkaline rock, and the fact that this differentiate borders against the limestone offers no real support to the theory. It is, moreover, clear that the magma has not been desilicated for huge volumes of it have crystallized to granite, unless the desilication was entirely local, a possibility which does not seem to accord with the idea that the limestone was absorbed as blocks which had sunk in the magma to great depths.

The writer has considered an alternative hypothesis which still maintains some connection between the limestone and the alkaline rock. The suggestion is that silica was subtracted from the magma locally for the formation of amphibolites from the surrounding limestone, a local desilication without important additions of lime from the limestone.[1] The occurrence of cancrinite could then be considered as due to introduction of CO^2 from the limestone, but this supposition, like Daly's, does not offer an explanation for the special abundance of sodalite in these nephelite syenites. There is no reason why an abundance of chlorine should be produced by interaction with limestone.

On the other hand, if it is supposed that the nephelite syenite belongs to the stage of great concentration of the volatile con-

[1] The quite similar suggestion recently offered by Foye appeared too late to receive adequate recognition in this paper, *Am. Jour. Sci.* (4), XL (1915), 430.

stituents of the magma, it is to be expected that the minerals precipitated would give evidence of richness in those volatile constituents which are known to be constituents of magmas. The minerals are, in the present case, sodalite and cancrinite, in other cases noselite and hauynite as well. Moreover, under this theory, this light residual magma tends to accumulate, during the course of differentiation by crystallization, in the upper and outer parts of the batholithic chamber, and in a limestone terrane it is especially likely to border on the limestone. This theory, then, assigns to the limestone no essential action in the formation of the alkaline types as is obviously true in other localities where limestone is absent in the country rock or present only in relatively small quantity. It is, for example, difficult to imagine how an occasional bed of limestone in a terrane consisting principally of siliceous gneisses could be considered a possible agent of desilication, for its absorption would entail simultaneous absorption of a much greater quantity of relatively siliceous material.

To return to the idea of the desilication of the magma, either localized or otherwise, through interaction with limestone in the Bancroft area, it may be pointed out that there are in this area many bodies of diorite of no inconsiderable size which one would expect to have suffered similarly, for they also have caused amphibolitization, etc., of the limestone. Indeed, the task set the limestone would seem to be much less arduous in this case than in the case of granitic magma. The reduction to nephelite of the polysilicate molecules represented in the alkaline feldspars would need to be preceded in the granitic magma by the binding of the quartz, whereas this would be unnecessary in the diorites. Nevertheless the diorite bodies apparently fail to show borders of nephelite-bearing rocks. They belong, not with the diorites, but with the quartz-rich rocks, the granites, as they should under the present conception of their origin.

Neither is the Bancroft area the only one that exhibits this intimate connection of the nephelite-bearing rocks with granites. Several cases have already been referred to in discussing the sequence of types and several more could be added. At this point only three others will be mentioned. The nephelite syenites

(canadites) and umptekites of Almunge, Sweden, are transitional both into alkaline granites and nordmarkites and also into normal sub-alkaline granites.[1] In the Bushveldt laccolithic complex, the succession, ultra-basic types, norites, granites, nephelite syenites is developed and Brouwer emphasizes a significant feature in this connection when he refers to the formation of "eenerzijds zeer kwartsrijke, anderzijds veldspatoïdvoerende gesteenten" by "dirrecte differentiatie." As a third example, it may be pointed out that Daly has himself detailed the evidences of a "genetic bond" between the Kruger nephelite syenites, malignites, etc., and the Similkameen granite.[2]

Normally, the nephelite syenites and their relatives appear, then, to fall naturally into a differentiation sequence, being intimately related to quartzose types, as the field evidence indicates and as chemistry would lead one to expect. It may, nevertheless, be reasonably considered probable that some nephelite rocks, especially melilite-nephelite types, may be formed by the method suggested by Daly.

Harker[3] has advanced the idea that the alkaline rocks owe their origin to a certain type of earth movement distinct from that brought into play during the formation of sub-alkaline types. Harker admits that the connection is not understood, but seeks to show that the distribution of the two branches is related to the great tectonic features of the earth. So many exceptions have been pointed out by Cross, Daly, and others to his general subdivision, with Becke, into Atlantic and Pacific provinces, that its validity will not be discussed further here. There remain, however, certain tendencies in that direction, among them the striking fact that the Rocky Mountain front in the United States lies approximately along a boundary between regions of dominantly alkaline and dominantly sub-alkaline rocks.[4] Harker has discussed this feature in some detail for the state of Montana. The general con-

[1] P. D. Quensel, "The Alkaline Rocks of Almunge," *Bull. Geol. Inst. Upsala*, XII, 157.

[2] *Geol. Survey Canada, Mem. 38*, Part I (1912), p. 459.

[3] *The Natural History of Igneous Rocks*, p. 93.

[4] Daly, however, describes nephelite syenite, etc., from the heart of the Cordillera (*Geol. Survey Canada, Mem. 38*, p. 488).

ception of the alkaline rocks advanced in the present paper appears to afford a rational explanation for this fact. It is considered that the alkaline rocks are derivatives of the same magma as sub-alkaline rocks, and belong to a late stage of concentration of the volatile constituents of the magma. They are light differentiates and therefore have a distinct *tendency* to occur as marginal and satellitic bodies *at a higher level* than their sub-alkaline co-derivatives. In those discrete mountain groups which lie east of the Rocky Mountain front in Montana, erosion has, as a rule, penetrated only to a level where the igneous intrusives are dominantly alkaline. Farther to the west, uplift and consequently depth of erosion are relatively greater; the present surface has penetrated, for the most part, below the level of the alkaline intrusives, and the principal exposures are of sub-alkaline types. Farther to the north, in the Rocky Mountain system in British Columbia, erosion has as yet penetrated only one considerable igneous body, the Ice River laccolith, and that, in conformity with the expectation of the general tendency postulated, is an alkaline body.[1]

If the suggestion is correct, then, this striking division into provinces is only in a remote manner connected with the tectonic feature, the Rocky Mountain front. Relative depth of erosion is accountable for the differences observed at the present surface.

It appears, moreover, that the general tendency toward a greater abundance of alkaline rocks in recent terranes as compared with ancient terranes is assignable to an accompanying tendency toward a greater depth of erosion in the ancient terranes.

Smythe, attacking the subject from a somewhat different viewpoint, has arrived at substantially the same conclusion as the writer with regard to the importance of mineralizers in the formation of the alkaline rocks.[2] Daly, too, appears to consider it possible that the CO_2 added when limestone is absorbed may be an important factor and this may perhaps be true in some cases. The writer would agree with Smythe in considering the production of

[1] J. A. Allan, *Geology of the Ice River District, British Columbia*, abstract of thesis, Massachusetts Institute of Technology, 1912, and *Geol. Survey Canada, Mem. 55*, 1914, p. 209.

[2] C. H. Smythe, Jr., *Am. Jour. Sci.* (4), XXXVI (1913), 46.

alkaline types entirely independent of absorption of foreign material in the great majority of cases and would assign the significant rôle to juvenile gaseous substances, principally water, concentrated in residual liquors in a natural way.

IS BASALTIC MAGMA THE PARENTAL MAGMA OF ALL IGNEOUS ROCKS?

GENERAL CONSIDERATIONS

In the foregoing pages an attempt has been made to give a rather full discussion of differentiation in igneous rocks and of the principles underlying it. A beginning was made with the discussion of the common association, in sill-like bodies where both top and bottom are exposed and all the relations clear,[1] of diabase with biotite granite and often several intermediate types. A specially notable case is that of the Purcell sills described by Daly and later by Schofield in greater detail. It was shown that the relations found are strictly those to be expected if differentiation takes place through crystallization under the influence of gravity. The relation of the biotite granites and related biotite-quartz types to the alkaline rocks was then discussed and it was shown that the same principles of derivation are applicable.

While no implication is intended in the foregoing that basaltic magma is always the parent magma of the igneous series given, and while the outline may equally well be regarded as a contribution to the study of the differentiation of dioritic magma or of granitic or other magmas, nevertheless the discussion does emphasize the fact that a great variety of igneous rocks, possibly all important types, could be derived from basaltic magma by differentiation under the appropriate conditions. Since the idea that basaltic magma is the parent magma of all igneous rocks has already found favor with some petrologists, it becomes advisable to discuss the matter in the present connection.

Of the visible igneous rocks of the globe the volume of salic types is many times that of femic types.[2] In view of this fact it may seem a bold step to express the opinion that basaltic magma

[1] A method of attack the importance of which Daly has long emphasized.

[2] See Daly, *Igneous Rocks and Their Origin*, p. 52.

is the primary igneous material from which all known igneous rocks are derived, yet it is a logical step. Any large salic body, say granitic, whose every exposed portion is simply granite tells us very little about itself. Such are the bodies which give salic rocks their great preponderance. It appears to be the prevailing opinion, seldom explicitly stated, perhaps, but certainly implied in description and discussion, that such bodies of granite were formed by the crystallization of granitic magma which always existed *as such*. The opinion is not based on any definite evidence to that effect but merely on a lack of direct evidence to the contrary. Such lack of evidence stands over against a mass of convincing and positive evidence of the origin of granites (and other salic types) which occur in bodies of such size (or shape) that their relations are clearly shown.

A broad survey of the Keweenawan eruptives of the Temiskaming–Lake Superior region lays bare the essential features of the differentiation of basaltic magma as it is controlled by the size of the body. The Keweenawan flows are overwhelmingly normal basalts. The quickly cooled smaller dykes and sills are principally normal diabase, sometimes olivine diabase. The sills of moderate thickness have diabase with micropegmatite interstices as a result of somewhat slower cooling. The sills of considerable thickness commonly have diabase with micropegmatite interstices and a small salic differentiate (with intermediate types) at their upper borders. The writer has seen several examples both in the sills of Gowganda Lake and in the Logan sills of the north shore of Lake Superior.[1] In the case of the huge sheetlike mass at Sudbury the salic differentiate at the top constitutes a considerable area of granite. It is fortunate for the geologic investigator that the Sudbury intrusive sheet lies in a basin-shaped structural depression. If it had assumed the form of an inverted basin, erosion might have exposed the granitic phase only and the derivation of the granite by gravitative differentiation would not have been revealed. It would then have passed muster as an ordinary granite batholith, and, no doubt, many batholiths (bodies without visible floors) are similar to the

[1] N. L. Bowen, Gowganda Sills, *Jour. Geol.*, XXVIII (1910), 658; Logan Sills, *Ontario Bur. Mines, Ann. Rept.*, 1911, p. 127.

Sudbury sheet, in method of intrusion, great horizontal extension, and stratiform arrangement of their differentiates, of which we see only the more salic. If in any case, basaltic magma collected in a chamber comparable in size with that occupied by the Sudbury sheet, but of considerable vertical instead of horizontal extension, it is unlikely that any amount of later disturbance or erosion to be reasonably postulated would bring to light anything but the light salic differentiate. How much more true is this of bodies of magma of very great dimensions! While, therefore, nothing in the foregoing forces the conclusion that great granite bodies are merely the light differentiate of a basaltic mass, nevertheless the conclusion is entirely consistent with the observed tendency which accompanies increasing size.

The features pointed out for the North American province described are not local. They are world-wide in their occurrence. Certain observations by Sederholm are pertinent in this connection. Speaking of the fundamental rocks of Finland, he says that abyssal rocks corresponding to almost every formation of effusive rocks of the granite family are easily found in the deeply eroded complex, but no *abyssal* rocks are found belonging to the diabase family, though rocks of this latter family have been erupted during every time of quiet sedimentation in Fenno-Scandia, either forming effusive beds or being intercalated between the strata of the sediments. He considers that the erupted diabases represent basic marginal phases of the common magma from which all the rocks were derived and that they were drained off before the acid portions because of their greater fluidity.[1] It is necessary under this assumption to imagine a marked differentiation of the magma while still liquid, and an arrangement of the differentiates in opposition to gravity. It is also necessary to imagine that in all cases the basaltic marginal phase happened to be drained off. The difficulties involved are entirely avoided if it is supposed that the original magma was basaltic (diabasic) and that where intruded in small bodies it formed, for the most part, sills and flows of undifferentiated diabase or basalt. Where it collected in large abyssal masses crystallization took place slowly. Crystals sank

[1] *Bull. Comm. Géol. de Finlande*, XXIII (1907), 108.

gradually as they grew in the liquid. The liquid passed through all intermediate compositions toward the granitic and fed at various stages the dykes and flows of the different types of porphyry, naturally later than the diabasic types. But in the *visible upper portion* of the very large bodies of the magma, only those products which were precipitated at the latest (and lightest), stage of the magma's history are represented, i.e., the constituents of the rocks of the granite family.

Moreover, it seems quite reasonable and consistent to believe that the descent of igneous rocks has not been different from that outlined above, even in the earliest stages of the earth's history of which we have any knowledge from actual rock outcrops. The rocks described by Sederholm belong among the oldest. In the Canadian shield also the colossal batholiths of the Laurentian were preceded by the basaltic outpourings of the Keewatin, and the same interpretation of their relation applies as that just given for the Scandinavian shield. In the basement complex of Rhodesia the contrasted volume of exposed acid and basic types[1] is attributable to the action of similar processes. It seems possible, then, to consider that basaltic magma is the original material of all igneous action of which we have any direct knowledge, and that all igneous rocks, even the huge areas of pre-Cambrian granitic rocks are differentiates of basaltic magma.

The objection might be raised that, in the more deeply eroded terranes such as some pre-Cambrian areas must be, erosion should have cut through the salic types and exposed their complementary rocks if the salic batholiths are really only the upper portions of bodies formed by differentiation of basaltic magma. In other words, one would expect to find areas of basic rocks of batholithic dimensions. The objection seems, however, to lose much of its force when carefully considered. The granitic differentiate of an originally basaltic magma may be as much as 10 or 15 per cent of the total differentiated mass.[2] Erosion would, therefore, have to penetrate 10 or 15 per cent of the depth of the igneous mass to

[1] F. P. Mennel, *A Manual of Petrology* (London, 1913), p. 105.

[2] Collins has, for example, estimated the aplitic portions of the coarser Nipissing intrusives as 10 per cent or more of the total (*Geol. Survey Canada, Mem. 33*, 1913, p. 65).

pass the granite. Presumably this has been accomplished in many cases and somewhat more basic rocks, granodiorite or diorite, have been encountered. There is an abundance of diorite in the "granitic" areas of the pre-Cambrian and possibly careful structural and petrographic work would reveal that this diorite underlay granite. This has already been shown to be true in the case of the Palaeozoic Saugus batholith of Massachusetts.[1] Seldom has sufficiently detailed work been accomplished to reveal such facts in those areas of the pre-Cambrian where igneous rocks dominate. In the case of very large bodies erosion might penetrate two or more miles and then reach only types not very different from granite, say granodiorite or quartz diorite, which are not distinguished from granite in a good deal of areal pre-Cambrian work. Probably only profound erosion would reach the more basic types and it may reasonably be doubted whether erosion is ever sufficient unless the igneous mass is favorably disposed, as it was in the case of the Duluth laccolith. It is true that great depth of erosion is sometimes believed to obtain in pre-Cambrian areas, but this appears to be often merely the attributing of great power to geologic forces in the distant past. On the contrary, when the structural evidence is examined there has often been found but moderate erosion. Thus, in the Thousand Islands region Cushing has shown that some batholiths have been barely de-roofed,[2] and in the Bancroft area of Ontario there are still remnants of effusive rocks, comagmatic with the batholiths, which were formed on the surface about the time of the intrusion of the batholiths. Clearly the surface at that time could not have stood at a level greatly different from that of the present surface. These are isolated cases, of course, but infolded patches of surface volcanic rocks in the batholithic pre-Cambrian areas are common enough to indicate that possibly these terranes have not suffered excessive erosion. Apparently, then, one would not expect erosion to have exposed areas of basic rocks of batholithic dimensions even if the granitic batholiths were formed by differentiation of basaltic magma. It is tentatively suggested, however, that it may be the greater erosion of pre-Cambrian ter-

[1] C. H. Clapp, *op. cit.*, p. 6.

[2] "Geology of the Thousand Islands Region," *N.Y. State Museum, Bull. 145*, p. 43.

ranes which has led to the exposure in those areas, and almost solely there, of large bodies of anorthosite which should under the present conception of its origin be a moderately deep-seated differentiate.

Another fact which has been advanced in favor of the idea that basaltic magma is the parent of all igneous rocks is its continual recurrence in terranes of all ages in the form of fissure eruptions.[1] It occurs likewise as dykes filling fissures related to the primary structures of all terranes, which dykes are indeed often the feeders of fissure eruptions. These occurrences indicate its sudden arrival from great depth without opportunity for differentiation en route. All other types of magma when occurring in dyke form tend rather to center about areas of batholithic intrusion, the seats of differentiation.

It may, perhaps, be considered that it is the great fluidity of basaltic magma which permits it to pour out freely in the manner referred to. If this were true it would seem that basaltic magma would be the commonest material of fissure eruptions, andesitic magma somewhat less common, dacitic magma less common still, and so forth. Apparently, however, the material of fissure eruptions is too commonly basaltic to agree with this supposition. It is this fact which suggests that it is the only magma which arrives at the surface undifferentiated and that other magmas are formed from it by differentiation when it collects in batholithic masses.

Some further support for the conception that basaltic magma is the parent magma of all igneous rocks is to be found in the mineral constitution of the rocks themselves. Granitic or any closely related magma could not give a differentiate of basaltic composition by the collection of its heavier minerals. Only dioritic magma might reasonably be expected to do so at any time, but it would be remarkable if it gave at nearly all times basaltic magma of approximately uniform composition. One would expect rather a marked variation, according to the opportunity for the sorting of crystals of different densities, in all rocks more "basic" than the parental magma. This is true only of all rocks more basic than basalt. Pyroxenites, peridotites, and here we should include anorthosites also, are notably variable in the proportions of their

[1] Daly, *Igneous Rocks and Their Origin*, p. 458.

characteristic minerals. There is no evidence of that tendency toward fairly uniform relative proportions of mineral constituents such as is exhibited in basalt, diorite, and so forth.

THE AVERAGE IGNEOUS ROCK COMPARED WITH THE PARENTAL MAGMA

The fact that the average composition of igneous rocks is not basaltic might, perhaps, be considered to preclude the possibility that basalt is the parental magma of all rocks.

Several calculations have been made of the average igneous rock. The calculation is essentially the averaging of existing rock analyses and gives only the average analyzed rock. Even if weighted according to the relative exposed abundance of types, it is to be noted that the figures obtained would represent only the average exposed rock. It should not be assumed that this average would represent the composition of the general magma from which all rocks were derived. Such an assumption ignores the evidence of such bodies as the Sudbury sheet, the Duluth laccolith, and many others which tell us that the upper part of an igneous body is much more salic than the magma from which it is formed, *especially if it is a large mass*. Consideration of this fact with reference to large salic bodies of which only the upper portion is visible makes it necessary to believe that the salic rock is only a light differentiate of the magma from which it formed. This nearly constant tendency of the exposed rock to differ from the magma from which it formed in a special direction makes the average of the exposed rocks differ from the general magma in the same direction. There is therefore nothing contradictory to known evidence in the statement that, though the average of analyzed rocks is tonalitic-dioritic, and a weighted average would be even more acidic, yet the general magma is more basic, viz., basaltic.

The same considerations apply to the average rock of any particular area. If this average is considered to represent the original magma, and if the composition of any large body of which only the upper part is visible enters into the average, the assumption is implicit in the result of the calculation that the whole of this body is identical with its upper portion. This assumption is unsafe. The earliest of the effusive rocks

which initiate the volcanic phase of the igneous activity of the region in question is more likely to represent the original magma. In the Christiania region of Norway, for example, the average composition of the rocks is somewhere near nordmarkite. If it is considered that all the rocks were derived from nordmarkitic magma, it is necessary, in order to explain the sequence of types, to imagine a differentiation while the magma was still liquid, as Brögger does, and a collection of the heavier basic differentiates toward the top. This conception Harker has rightly described, in a different connection, as "wholly chimerical,"[1] but one might refer in a similar manner to the deep-seated magma basin, stratified according to density, as it might be, but from which, *in the usual case*, "the *earlier* intruded magmas are drawn from the *lower* levels."[2] On the other hand, if it is assumed that the original magma was the gabbro which forms the earliest extrusives, the rocks of the Christiania region seem explicable as the result of gravitative differentiation increasing in importance with the size of the bodies and emphasizing the alkaline and salic types in the exposed portions of the larger bodies. In the very closely related Julianehaab region Ussing has called special attention to "the contrast between the mode of occurrence of the dense, gabbroid rocks and the specifically lighter, more acid rocks," the former as dykes of small volume and the latter as batholiths, or rather the upper part of batholiths.[3]

THE EARLIER STAGES OF IGNEOUS ROCK EVOLUTION NOT REVEALED

The facts which have been pointed out in favor of considering basaltic magma the parent of all igneous rocks do not, of course, definitely prove the case, yet they appear to establish a strong presumption in its favor. The geologic record makes it necessary to imagine a source of basaltic magma beneath all parts of the surface of the earth throughout recorded time, and a great many facts indicate the derivation of all other magmas from the basaltic. What the antecedent stages which permitted the formation of this source of basaltic magma may have been is not revealed in the record. Consideration of these early stages would lead one into

[1] *Op. cit.*, p. 317. [2] *Ibid.*, p. 330 (italics are mine). [3] *Op. cit.*, p. 308.

cosmogony, which subject it is desired to avoid in this paper. It may be noted, however, that the existence of a source of basaltic magma does not necessarily imply a liquid layer and possibly not even a basaltic layer, since it is conceivable that disseminated basaltic liquid might have been generated as occasion demanded by some sort of selective fusion of heterogeneous non-basaltic material. This suggestion is not offered as an expression of opinion, but merely as an indication that belief in the continuous existence of a source of basaltic magma does not necessarily force one to prefer either the view that the earth was once molten or the view that it has always been a relatively cold body. Until the petrologist finds in his own field some reason for advocating the one or the other view, there is little need of his expressing a preference. Neither is it necessary for the petrologist to express an opinion as to the physical condition of the earth's interior, whether magmas come from great depth or moderate depth, whether they are generated as a result of some mechanical production of heat or have persisted from a once-molten earth. He may reasonably start with magma, however produced, and with such a magma or magmas as the geologic evidence appears to dictate.

THE NORMAL LINE OF DESCENT

The facts indicating the parental nature of basaltic magma have been detailed in the foregoing. As already stated, they are not considered as proving that basaltic magma plays this rôle, but rather as constituting a strong plea for the inclusion of this idea among the petrologist's working hypotheses. Especially is this desirable when a conception is gained of a process whereby igneous-rock series can be derived from basaltic magma. This process of evolution, through the action of crystallization differentiation, has already been stated in detail, with emphasis, for the most part, on its physico-chemical aspects. Consideration will now be given to some of its geological aspects.

In the following an outline of the conception of the igneous rocks here advanced is presented. It may serve as a summary of the fuller discussion presented in the preceding pages. Being in schematic form, it is necessarily somewhat rigid and is not to be interpreted without due reference to the discussion in the text.

I

COURSE FOLLOWED BY LIQUID AS A RESULT OF REMOVAL OF CRYSTALS

basaltic
↓
dioritic
↓
granodioritic
↓ ↓
granitic (basanitic)
↓ ↓
foyaitic (foyaitic)

(The career of the liquid may end at any of these stages on account of its complete freezing and consequent cessation of removal of crystals.)

II

MATERIALS FORMED BY ACCUMULATION OF CRYSTALS (ROCKS)

Extreme sorting.—Peridotites, pyroxenites, anorthosites, and other "anchimonomineralic" rocks.

Little sorting.—Any type formed by the freezing of the liquid at any of the stages in I, in a position where there has been accumulation, great or small, of one or more of the kinds of crystals which have recently separated from the liquid.

Principal Products of the Slow Crystallization of Basaltic Magma

Increasing concentration of volatile constituents and falling temperature ↓

Stage		
1.	(spinellids) magnesia-iron olivine	
2.	magnesia-iron pyroxene	calcic plagioclase
3.	lime-magnesia-iron pyroxene	calcic plagioclase
4.	hornblende	medium plagioclase
5.	biotite, quartz, orthoclase	medium plagioclase
6.	biotite, muscovite, quartz, orthoclase	sodic plagioclase
7.	alkalic: hornblende, quartz, or pyroxene	orthoclase, sodic plagioclase, or microcline
8.	alkalic: hornblende, iron olivine, or pyroxene	orthoclase, sodic plagioclase, or microcline
9	alkalic: hornblende, nephelite, or pyroxene	orthoclase, sodic plagioclase, or microcline
10.	pyroxenes, corundum, nephelite, sodalite	orthoclase, sodic plagioclase, or microcline
11.	pyroxenes or olivine, analcite	orthoclase, sodic plagioclase, or microcline

The preceding outline is intended to represent the usual case. The period of crystallization of any stage is somewhat later than that of the stage above it. The crystallization of a mineral placed under any stage is essentially simultaneous with that of the other minerals grouped with it. There is, of course, considerable overlapping from stage to stage; indeed, the division into stages is purely arbitrary, for the process itself is perfectly continuous.

The writer has some hesitation in presenting this very definite statement concerning crystallization, for he knows full well that it cannot be absolutely correct. Nevertheless, it is believed that if our knowledge of the subject were complete, the final correction of the statement would be principally an elaboration rather than an alteration. In presenting the foregoing scheme, the purpose is chiefly to emphasize the point of view from which the crystallization of a magma is to be attacked. The great difference should be realized between the simple group of minerals which results when a magma is crystallized quickly and the long series of products which may result from slow crystallization. The fundamental controlling influence of the plagioclase mix-crystal series must be recognized; also the fact that the minerals precipitated give clues to certain equilibrium reactions in the liquid. Ferromagnesian material in one form or another must appear at all stages of precipitation. If a chemist has a mixture of, say, potassium and sodium salts, he has yet to discover a method of cooling or evaporation whereby *all* the sodium salts can be removed from the solution so long as any solution is left.

The great lowering of the temperatures of crystallization of granitic magma as the result of the concentration of volatile constituents has often been emphasized, but the converse is worthy of equal emphasis. The relatively great concentration of volatile substances in granitic magma is the result of its low temperature of crystallization and follows as a necessary consequence of the long-preceding period of crystallization in virtue of which alone granitic magma comes into being.

VARIATIONS FROM THE STATED SCHEME OF CRYSTALLIZATION

In presenting the schematic statement of the progress of crystallization the writer does not intend to imply that this sequence is

rigidly adhered to in every case of slow crystallization of basaltic magma. The plan of presenting the subject—that of offering experimental evidence bearing on the questions and then deducing therefrom the crystallization of a magma—has led naturally to the statement of crystallization given above. This may be regarded as the normal sequence, for, considering the volume of rock types produced, it is probably the most important. Any other succession of types may be regarded as a variant from the above. In this connection it is intended to discuss what appear to be two principal variants and to suggest that the effects of pressure probably adequately explain these variants. The effects are not those of pressure *per se*, for these are probably altogether insignificant, but rather of pressure in so far as it affects the retention of volatile constituents, especially water.

The sequence gabbro-diorite-quartz diorite-granodiorite-granite-alkaline types expressed in the tabular statement given is that normal to the Mesozoic-Tertiary intrusives of the Cordilleran region of North America. The types characteristic of the pre-Cambrian intrusives of the Adirondacks and adjacent regions of Canada are rather gabbro-diorite-syenite-granite-alkaline types. If we regard the nature of the plagioclase as a measure of the stage of crystallization or the degree of concentration of the liquid residue relative to the original volume of magma; it is clear that the types of the eastern area exhibit a delaying of those reactions, characteristic of the presence of water, which result in the separation of significant amounts of biotite and quartz. It appears, therefore, that at any stage, representing a certain degree of concentration of the residual liquid with respect to the original magma, the active mass of water was less during the development of the eastern types than during that of the Cordilleran types. In any individual case it would be impossible to refer such a difference in the activity of water definitely to a difference of external pressure, but that this is the kind of effect which would result and no doubt has resulted in many cases is hardly to be questioned.

The production of quartz and biotite in the presence of water results in large part from the breakdown of $KAlSi_3O_8$ molecules. A low value of the active mass of water, sufficient to reduce this

reaction to a minimum, should considerably advance the period of precipitation of $KAlSi_3O_8$ as orthoclase.[1] This may be the principal factor controlling the essexite line of descent consisting of gabbro, essexite, augite syenite, and the alkaline types common to all lines of descent. Thus the precipitation of considerable orthoclase takes place at a stage when the plagioclase is still strongly calcic in the case of essexite, and the delaying of those reactions characteristic of great "activity" of water is still well marked at the augite syenite stage, when the feldspar is already entirely alkalic whereas the dominant ferromagnesian mineral is still a typically anhydrous pryoxene. Even in this series, however, the water finally makes its presence felt as its concentration in the residual liquid increases, with the resultant production of feldspathoid-bearing and of quartzose types.

An apparent association of rocks of the essexite line of descent with specially intensive tensional faulting (e.g., Christiania and Julianehaab) lends support to the foregoing conclusion that this line of descent is controlled by low pressures resulting in lessened "activity" of water.[2] The rocks of this series as a whole have been termed alkaline rocks, and if alkaline varieties belonged only in this line of descent, Harker would probably be correct in concluding that alkaline rocks are formed as the result of a certain definite kind of tectonic movement. But whatever line of descent is followed, there comes a time under appropriate conditions when the concentration of volatile constituents brings about the production of such alkaline rocks as nephelite syenite.

The essexite, augite syenite line of descent probably approaches the extreme of low "activity" of volatile constituents at the early stages, and the quartz diorite line of descent probably approaches the extreme of great "activity" of volatile constituents at these stages. Between the two there is presumably every gradation.

[1] The calculations given by Iddings in *Igneous Rocks*, I, 152, are significant in this connection. There he shows that the same analysis may be considered to represent either a rock characterized by the hydrous minerals, mica and hornblende or a rock with anhydrous minerals, pyroxenes. In the latter case the amount of orthoclase is nearly doubled.

[2] It may well be, however, that volatile substances are as abundant in magmas of this series as in any others but that water is relatively an unimportant fraction.

These differences are to be connected in part with differences in external pressure, but the nature of surrounding rocks and, to some extent, original differences in the magmas are to be considered as well.

MONOMINERALIC ROCKS

The formation of "anchi-monomineralic" rocks is possible in the earliest stages (and apparently only then), whatever line of descent is followed, if conditions favor the collection of the early crystals, principally olivine, pyroxene, plagioclase, and iron ores. The more or less perfect sorting of these crystals which results in the formation of dunite, pyroxenite, and anorthosite should be expected normally only in a large body of magma which cools very slowly through the early stages of crystallization. There must be a considerable period during which olivine is separating alone and also a considerable period during which pyroxene and plagioclase, though separating together, for the most part, form only a small fraction of the total mass (liquid and crystals), so that the pyroxene crystals may assert their greater density without much interference from the lighter plagioclase crystals. It appears, indeed, that plagioclase crystals may at the earlier stages of crystallization be only very slightly heavier than the liquid at most and possibly even somewhat lighter. This seems to be the promising period for the collection of plagioclase crystals nearly free from pyroxene. At a later period, provided there is sufficiently slow cooling, these plagioclase crystals will sink and the normal effect on the composition of the liquid will ensue. The formation of syenitic and granitic differentiates is therefore not precluded by the formation of anorthosite, i.e., anorthosite is not the result of an alternative line of descent. This fact is shown by the Duluth gabbro laccolith, probably by the complex-gabbro, anorthosite, syenite, etc., in the Long Lake quadrangle, New York, described by Cushing;[1] by the norite, anorthosite, banatite, granite, etc., of the Ekersund-Soggendal region of Norway;[2] and by a rather similar association in the Nordingrä region of Sweden.[3]

[1] *N.Y. State Museum, Bull. 115*, 1907.

[2] Kolderup, *Bergens Museums Aarbog*, 1896, No. V.

[3] José M. Sobral, *Contributions to the Geology of the Nordingrä Region, Upsala*, 1913.

Though the separation of immiscible liquid fractions has already been fully discussed and reasons given for rejecting it in silicate liquids, a certain phase of the subject may be pointed out briefly in this connection. Some have supposed that individual minerals may separate from the magma in the liquid state with the consequent possibility of the formation of a monomineralic rock. Thus the formation of anorthosite has been considered due to the local collection of immiscible plagioclase portions. If plagioclase did separate from the magma as a distinct phase, it would no longer be in solution in anything and therefore must acquire its own individual properties, one of these being a definite temperature or temperature of range of melting. Thus the plagioclase Ab_1An_2 could separate from the magma as a liquid, if at all, only above 1490°, and common olivine only above some such temperature as 1700°. These temperatures need only be mentioned in order to prove the impossibility of such a process. Any immiscible liquid phase separating from a magma would necessarily be a solution of minerals capable of existing alone as a liquid at the temperature concerned, for the presence of other liquid *as a separate phase* affects its properties not at all.

Winchell has described the collection of *crystals* for the formation of anorthosite masses in all its stages in the Duluth gabbro of Minnesota,[1] and the writer has seen the incipient stages of the same process in neighboring regions of Canada.[2]

There are, moreover, certain features of anorthosites which strongly confirm the conclusion that they are formed simply by the collection of plagioclase crystals. When plagioclase crystals have collected locally in a magma in sufficient concentration to render the rock an anorthosite, the amount of interstitial liquid, which is of mixed composition, must be reduced to a minimum. The movement of such a mass involved in its reintrusion into surrounding rocks would necessarily involve much breaking up of the plagioclase crystals. Likewise one would hardly expect a rock so generated to form effusive masses. Corresponding with these expectations we

[1] N. H. Winchell, *Geol. and Nat. Hist. Survey of Minnesota, Final Rept.*, V (1900), 66.

[2] N. L. Bowen, *Ontario Bur. Mines, 20th Ann. Rept.*, 1911, p. 127.

note the common protoclastic structure of anorthosite, and the non-occurrence of an effusive equivalent. It may be noted, moreover, that some of the features of monomineralic rocks pointed out by Vogt,[1] the enrichment of peridotites in magnesia, of anorthosite in lime, and so forth, are explicable only on the basis of their formation by the collection of early crystals.

THE ORDER OF INTRUSION

If the change of composition of the liquid is as shown in the scheme presented under I, p. 75, the tapping of the batholithic reservoir at successive stages will usually realize "the normal order of decreasing basicity" in the order of intrusion. Quite commonly the sequence observed in batholiths themselves is simply a sequence of consolidation, differentiation having taken place practically *in situ*. It is, however, not to be expected that this order will be universal. If the hypabyssal rocks of a given area were fed from two adjacent batholithic reservoirs which at any given time were at different stages in their career of crystallization, it is easy to see that the exposed rocks might exhibit no system in the matter of change of composition in successive intrusions.

The upward intrusion of the material in a single reservoir may also give results which depart from the "normal order." If the magma is forced upward at a time when the upper part is largely liquid and the lower part contains a large proportion of the heavier early minerals with sufficient liquid to render it eruptible, the more "basic" type should follow after the more salic type. The case of Mount Johnson where essexite follows pulaskite is apparently an example of this phenomenon.[2] It is certain that the predominance of the order of decreasing basicity which has led to its designation as the normal order is to be expected if crystallization as discussed in this paper is the controlling factor in differentiation. Brögger's conclusion that the *Differentiationsfolge* is parallel to the *Kristallisationsfolge* is correct, the reason being simply that differentiation is the result of crystallization. That the same is true of the *Eruptionsfolge* is commonly, though not necessarily, true also.[3]

[1] *Op. cit.*, pp. 19–49; also summary statement of same by Harker, *op. cit.*, pp. 372–74.

[2] F. D. Adams, *Jour. Geol.* XI (1903), 281.

[3] *Eruptivgesteine des Kristianiagebietes*, II (1895), 175.

Instead of decreasing basicity or increasing acidity it would be more correct to say increasing alkalinity, for in the later stages increasing acidity of the liquid does not hold. Increasing alkalinity appears, however, to be maintained throughout.

The question of the fate of sinking crystals may be discussed at this point because it bears directly on the order of intrusion. Some have supposed that solution of crystals formed in the cooler upper portion will take place freely in the warmer lower portion into which they may settle. It is even imagined that complete re-solution of all the crystals may take place with the formation of a magma basin entirely liquid, but, in virtue of the foregoing action, much enriched in its lower parts in the products of early crystallization. A certain amount of the re-solution postulated must indeed take place, but there is a limit to the process. The re-solution of crystals would usually require a relatively large amount of heat and the heat available is limited on account of the relatively small specific heats of silicate liquids and on account of the fact that the actual downward increase of temperature must be small, for significant sinking of crystals takes place only in those parts of a magma body that are slowly cooled and therefore exhibit small temperature gradients. The re-solution of a small proportion of crystals by a certain layer of the magma should lower its temperature very considerably and, at the same time, raise the temperature at which the liquid becomes saturated with crystals. Shortly, therefore, the liquid is cooled to the temperature at which, in its slightly enriched condition, it is saturated with these crystals and the process of re-solution ceases. The extreme condition of complete re-solution of crystals approximately keeping pace with their arrival from higher layers could scarcely be even approached. Whatever crystals sink from upper layers remain, for the most part, as such.

This deduction is entirely confirmed, indeed it finds its geologic expression in the "normal order of decreasing basicity." If it were common to have magma basins still entirely liquid but much enriched in their lower portions in basic material through re-solution of crystals, the normal order would be from acid to basic, for all portions of the magma would be freely eruptible and the upper,

more acid portion would commonly precede the basic portion. But, on account of the fact that crystals accumulate as such in the lower portions, these portions have little eruptibility and such intrusions as may occur come from the still liquid upper portion almost exclusively. Successive intrusions therefore commonly exhibit the decreasing basicity which this liquid portion experiences. Some cases of reversal of the normal order may, perhaps, be reasonably attributed to the intrusion of liquid from the middle portion of the reservoir bearing a relatively small proportion of crystals and following closely after the liquid from the upper portion.

It is not to be assumed from the foregoing discussion that the liquid portion itself from a lower layer would not have a different composition from that in an upper layer. The collection of the early crystals in the lower layers causes the liquid in those parts to follow a different course from that followed in an upper layer, even although the liquids are freely miscible to a homogeneous liquid. It is the attempt of the liquid in different parts to maintain equilibrium with its *immediate* surroundings that determines the different courses followed. The bearing of the existence of liquids of somewhat different composition in contiguous layers on the formation of rocks exhibiting primary banding has already been discussed.

CHILLED BORDER PHASES

Chilled border phases have already been referred to several times, especially the formation of a basic border by restriction of differentiation due to sudden chilling. Thus the formation of a diorite border phase about a granite is explained as due to completion of crystallization near the border at stage 4 (see p. 75) and continuance of crystallization and removal of crystals in the more slowly cooled part removed from the border until stages 5 and 6 have been attained. The border phases produced by such chilling are, however, not necessarily basic. Thus in some cases the chilling might cause completion of crystallization toward the border at stages 6–7 with the formation of a quartzose type, a granite, whereas the more slowly cooled part might, by removal of crystals, continue its crystallization through stages 8 and 9 with the formation of a nephelite-bearing type. It seems possible that the quartzose

border phase occurring about the nephelite syenite of Red Hill, New Hampshire, was formed in this manner. Pirsson and Washington point out that contact chilling is shown by the finer grain of this quartzose phase.[1] A more salic nature of the border phase when formed by chilling (not by the squeezing out of a pegmatite-like fringe) should in fact be common in rocks belonging to this stage of precipitation, i.e., to associations of nordmarkite, pulaskite, foyaite, and related types. It is apparently principally among such types that acid border phases have been observed, an especially clear case being that at Almunge in Sweden where nordmarkite occurs as a border phase about umptekite and nephelite syenite.[2]

THE RÔLE OF ASSIMILATION

In the foregoing discussion of the igneous rocks assimilation has not been mentioned as an essential process in the production of diversity of rock types. It is believed that differentiation of basaltic magma after the method proposed is the essential process and that a basaltic magma may and commonly does give a salic differentiate, say granitic, without having assimilated salic material. If, as is believed, basaltic magma is the original material of all igneous action with which we are acquainted, then, in the beginning, there could, of course, have been no salic material available for assimilation. Nevertheless, after the lapse of time, the formation of a great diversity of rocks by differentiation from basaltic magma was accomplished and then a magma might at some stage in its career make contact with, say, a salic rock. A certain amount of assimilation might ensue. A magma might also assimilate some material formed from igneous rocks by atmospheric agencies, i.e., sedimentary rocks. It is the purpose of this part of the paper to discuss the effects of such assimilation.

As a matter of fact, plain evidence is to be found in the field that magmas do assimilate, especially when they occur in the large bodies commonly termed batholiths. Sometimes batholiths have, indeed, a chilled contact against their country rock and in such a case little assimilation can be admitted. This appears to be

[1] *Am. Jour. Sci.* (4), XXIII (1907), 276.

[2] Quensel, *op. cit.*, p. 161.

especially true of batholiths which crystallized at no great depth from the surface and therefore against cold rocks.

At greater depth, however, the magma is likely to have greater effect on its country rock. The surrounding rock may become thoroughly impregnated with magmatic material.[1] Blocks of the country rocks which have become broken off may become similarly impregnated and a gradual mixing of the materials at their borders with the magma may bring about finally a homogeneous mixture of the country rock and magma. If this crystallizes as such, it gives a hybrid rock. When the rock invaded is an igneous rock the hybrid may be identical with a normal igneous rock intermediate in composition between the two. If the two rocks involved lie far apart in the igneous series, say granitic magma invades peridotite, a hybrid of composition not represented among normal igneous rocks may be formed. When the rock invaded is a sedimentary rock certain minerals normally belonging to the metamorphosed sediment, garnet for example, may appear also in the hybrid.[2]

However, the formation of an obviously hybrid rock should, apparently, be the normal result of assimilation. Some petrologists have assumed that as a result of assimilation the tendency toward differentiation is so increased that the free differentiation which follows destroys the simple hybrid relation. This opinion is based in part on the assumption that rocks mutually lower each others' crystallization temperatures. As a matter of fact, if two rocks were mixed the temperature range of solidification of the mixture would in general be intermediate between the corresponding range of the individual rocks. This refers of course to the temperature range of solidification if no crystals are removed. If crystals are removed the temperature range of crystallization of the syntectic magma will be continually extended precisely as the temperature range of the original magma would have been extended by the same process. The question of the effect of assimilation on differentiation really reduces itself, then, to the question of its effect

[1] C. N. Fenner, "The Mode of Formation of Certain Gneisses in the Highlands of New Jersey," *Jour. Geol.*, XXII (1914), 602.

[2] Cf. Harker, *op. cit.*, p. 338.

on the possibility of this continual offsetting of the composition of the liquid with its accompanying increased temperature range of crystallization.

On account of the cooling effect of the dissolution of solid rock the process should be limited from that cause.[1] Another important consideration is the effect of the addition of the foreign material on the fluidity of the magma. Exception must be taken to the statement, sometimes made, that, as a result of assimilation the magma becomes more fluid. In so far as the temperature is lowered the magma becomes less fluid. In so far as the composition of the magma is changed the fluidity may increase or decrease, depending on the nature of the material added. In the case of the absorption of a salic rock by a basic magma there would certainly be a very important decrease of fluidity from both the above-mentioned causes. The result would here be a marked restriction of differentiation and not a tendency to promote it.

The opinion that the fluidity of a magma is increased by the dissolution of foreign material is probably the result of a failure to distinguish between *fluidity* and *fusibility*. It is true that the addition of one substance to another nearly always increases the *fusibility*, i.e., there is a mutual lowering of melting-point, but even this principle must be applied with caution and with due regard for the exact nature of the dissolving liquid and the dissolved material. Thus the addition of tin to lead lowers the temperature at which solidification begins. The temperature at which solidification is complete is, moreover, lower than the melting-point of either of the metals separately. It is true also that if some bismuth is added to this mixture of lead and tin the temperature of beginning of solidification and the temperature of completion of solidification will be still further lowered. But if to this mixture of lead, tin, and bismuth a mixture of any two of these, say lead and bismuth, is added, the temperature of beginning of solidification may be either raised or lowered, depending on proportions in the mixtures, and the temperature of completion of solidification will be affected not at all. The solution of a foreign rock in a magma

[1] Normally one would expect the cooling effect to be great, the specific heats of liquid silicates being so small as compared with latent heats.

is in a general way analogous to this latter case. It is an addition to the magma of materials which it already contains. Either a raising or a lowering of the temperature of beginning of crystallization may result as in the case of the alloys mentioned. On account of the prevalence of solid solution among the constituents of rocks even the temperature of completion of crystallization may also be either raised or lowered.

Experiments along this line have been made by Petrasch. In one of these, two parts of limburgite were mixed with one part of granite and a supposed lowering of freezing temperature found.[1] But the melts in this case cooled partly to glass and the so-called *Erstarrungspunkt* is merely the observer's opinion as to the point at which this glass became sufficiently viscous to be called a rigid body. This temperature has nothing to do with the temperature of change from liquid to solid, i.e., crystals, and this change is the significant factor in the present connection, for only in the case of a magma which cooled sufficiently slowly to crystallize can the possibility of its having absorbed surrounding rocks be even seriously entertained. Probably the actual temperature range of crystallization of the mixture mentioned above would be intermediate between the corresponding ranges of the individual rocks, a condition which would certainly be true for the mixing of any two rocks in which feldspar mix-crystals were important constituents. This may be taken as a very general, though possibly not universal, feature of the mixing of polycomponent rocks.

Neither increased fluidity nor increased fusibility can be safely postulated as an ever-present aid to the continuance of assimilation and to the differentiation of the syntectic.

It may therefore be repeated that the result of assimilation should normally be an obviously hybrid rock. Recent studies in the Pyrenees, where assimilation on a large scale has been claimed, have led to the conclusion that assimilation is limited in amount and that the rocks produced are unmistakably hybrid.[2]

[1] *Neues Jahrb.*, Beil. Band XVII (1903), 508.

[2] See O. H. Erdmannsdörffer, "Petrographische Untersuchungen an einigen Granit-Schieferkontakten der Pyrenäen," *Neues Jahrb.*, Beil. Band XXXVII (1914), 740.

But there are doubtless some cases in which the syntectic magma formed by assimilation crystallizes only toward its borders as a hybrid rock, whereas, in adjacent portions of the magma the syntectic crystallizes sufficiently slowly to permit of differentiation and, possibly, the masking of hybridism. It is probable that in some cases a magma has locally completely incorporated an amount of foreign material equal to a small percentage of its own mass, and the question arises as to the effect on the course of differentiation.

It is clear that if the foreign material is igneous, the syntectic magma resulting will crystallize according to the general scheme outlined for a normal magma. No unusual result is possible. The only effect will be such that if the material added is, say, granitic, the granitic differentiate will be correspondingly increased, provided, of course, cooling is sufficiently slow to permit the attainment of the granitic stage.

If the foreign material is of sedimentary origin the result will in general be not very different. Even when the sedimentary rock has a composition considerably removed from that of any possible igneous rock nothing is added to the magma that it does not already contain. But since the added material contains the various oxides in proportions very different from those of the magma, the result will be a rearrangement of equilibrium in the liquid. Certain combinations already present will be increased in amount, others diminished. When only a moderate amount of material has been added, no special result will ensue. Crystallization will follow the normal course described, but at certain stages there will be increased or decreased precipitation of some of the normal minerals according to the nature of the material added. The result will not be distinguishable from any normal suite of igneous rocks.

In an extreme case, however, a great increase may result in certain combinations which normally do not occur in the magma in sufficient concentration to be represented among the minerals precipitated and are therefore not generally found as crystals in igneous rocks. In such a case one or more of these combinations may exceed its solubility at some stage in the history of the magma and, being precipitated, will be added to the normal minerals. Such combinations are likely to be the same as those which form in the

zone of contact metamorphism or in the hybrid rock already referred to. Thus garnet is likely to be precipitated at some stage in the crystallization of such a magma, also scapolite, sillimanite, and even calcite when the magma is not very rich in silica, as in the case of foyaitic magma. It may well be, also, that some melilite rocks are formed by the crystallization of a syntectic magma formed by the solution of limestone, as Daly has suggested.[1] The precipitation of such unusual minerals is, however, usually only an incidental feature in the crystallization of the magma. The whole course of crystallization will probably still be dominated by the feldspars and the continual offsetting toward the more alkalic feldspars will be maintained. Probably, then, the crystallization of such magmas will tend to pass down through the same intermediate stages to the granitic and into the alkalic stage with the occasional appearance of some unusual mineral and a slightly increased or decreased amount of precipitation of some of the normal minerals at various stages.

If the absorption of any considerable amount of limestone by a magma can be admitted, it may be expected to have a very unusual effect upon the magma, as Daly has suggested. The taking of silica from feldspar molecules by the lime and the consequent production of feldspathoid molecules might well be supposed a reasonable possibility. Some alkaline rocks may, perhaps, be so generated, but on an earlier page reasons have been presented for believing that normally the alkaline rocks enter into an eruptive sequence as the products of differentiation solely.

SUMMARY AND CONCLUSION

It is desirable now to summarize briefly the principal conclusions reached. Consideration of the factors limiting its scope has led to the decision that assimilation is, relatively speaking, an unimportant factor in the production of the diversity of igneous rocks. For palingenetic action in its still more extreme form, involving the direct refusion of sedimentary terranes, no support is found. Such action would often give rocks of mineral composition never found in an igneous series, rocks consisting mainly of

[1] R. A. Daly, *Igneous Rocks and Their Origin*, p. 436.

diopside and quartz from a quartzite-dolomite terrane, for example. On the contrary, it is believed by the great majority of petrologists that the rocks of any area vary among themselves in a systematic manner which indicates derivation from a common stock through some systematic process of differentiation from that stock.

The decision is reached that this differentiation is controlled entirely by crystallization. The sinking of crystals and the squeezing out of residual liquid are considered the all-important instruments of differentiation, and experimental evidence is adduced to show that under the action of these processes typical igneous-rock series would be formed from basaltic magma if it crystallized (cooled) slowly enough. The characteristic occurrence of basaltic magma as regional dykes and as the material of the great fissure eruptions is considered evidence of the primary nature of basaltic magma. It is concluded, therefore, that most, if not all, igneous rocks have probably been derived from basaltic magma, the processes of differentiation that have been pointed out above emphasizing the lighter, more salic and alkalic differentiates in the upper portions of very large, slowly cooled bodies.

In some of its more fundamental aspects the conception of the igneous rocks reached is, therefore, closely related to that advanced by Daly. Basaltic magma is the primary material of all post-Keewatin igneous action according to Daly. The more immediate derivatives of this magma, peridotite and augite andesite, he considers to be formed through gravitative differentiation, which he formerly believed to be due to the sinking of crystals, though he now leans toward the formation of immiscible liquid portions. For the formation of more remote derivatives, diorite, granodiorite, granite, nephelite syenite etc., however, he considers that in each case assimilation of a special kind of foreign material, the acid shell of the earth or various types of sediments, must first be accomplished and has therefore introduced the idea of stoping with abyssal assimilation or assimilation at unobservable depths. Here the present conception diverges radically. The reasons for assuming abyssal assimilation, or any kind of assimilation on the scale advocated by Daly, are considered to be entirely removed when it is shown that the types enumerated above and probably

all other igneous rocks could be derived from basaltic magma by differentiation alone. Incidentally the necessity for assuming a granitic shell of the earth of totally different origin from all later granites is eliminated. Complete accord with Daly is, however, reached with regard to the importance of gravitative differentiation and the importance of restriction of differentiation at the contact in the production of contact phases, commonly, though not always basic phases.

In conclusion, the writer desires to express his indebtedness to many of his colleagues at this laboratory, physicists and chemists as well as petrologists, for helpful discussion of some of the problems treated.